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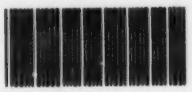

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FIBRE OPTIC AIRCRAFT FUEL GAUGE

Prepared for

Transportation
Development Centre
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FIBRE OPTIC AIRCRAFT FUEL GAUGE

by

J. W. Snow, S. H. Woodside, and P. D. Colbourne

Focal Technologies Incorporated

January 1990

The contents of this report reflect the views of Focal Technologies Incorporated and not necessarily the official views or opinions of the Transportation Development Centre of Transport Canada.

Un sommaire en français de ce rapport est inclus avant la Table de matières.

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16. Abstract

The feasibility of a fibre optic continuous liquid level sensor for aircraft fuel quantity measurement (FQM) was examined. Such a sensor offers certain advantages in terms of safety and performance by providing a spark-free, electromagnetic interference (EMI) immune and potentially more accurate alternative to conventional capacitance fuel probes. Two sensor configurations based on the principle of total internal reflection were developed and tested: one based on fluorescent fibre, the other on notched rods. A common lead insensitivity scheme was also developed for both sensors to be able to differentiate the sensor response from other time varying system changes. An automated, instrumented test tank facility was constructed to evaluate the sensors in terms of key performance criteria against a generic FQM specification developed from inputs received from various airframe manufacturers and from relevant equipment standards. Resolution of 5 mm in 1 metre was achieved along with a long term drift of less than one percent. The outstanding development items relate to materials issues for optical, mechanical and environmental performance including fouling of optical surfaces and condensation.

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16. Résumé

Ce rapport fait état d'une étude de faisabilité d'un capteur à fibres optiques pour le contrôle permanent et le mesurage du niveau de carburant (MNC) dans les aéronefs. Ce type de capteur offre certains avantages relativement à la sécurité et au rendement, car il s'agit d'un dispositif anti-étincelle, à l'épreuve des interférences électromagnétiques et qui constitue un substitut potentiellement plus précis que les indicateurs classiques de mesure de carburant par capacité. A cet effet, les chercheurs ont mis au point et fait l'essai de deux configurations de capteur dont le fonctionnement repose sur le principe de la réflection interne globale: le premier étant un capteur à fibres fluorescentes et le second un capteur à tige rainurée. Afin que ces deux dispositifs puissent différencier leurs réponses des autres effets temporalisés du système, on a également mis au point un montage insensible à conducteur commun. De plus, on a construit un réservoir d'essai automatisé et muni des instruments nécessaires pour évaluer les principaux critères de fonctionnement de ces capteurs, en regard des spécifications générales de MNC établies à partir des renseignements recueillis auprès de différents avionneurs et selon les normes pertinentes. Les expériences ont permis d'observer une résolution de 5 mm au mètre et une dérive à long terme de moins de 1 p. 100. Les problèmes en suspens ont trait au rendement optique, mécanique et environnemental des matériaux utilisés, de même qu'à l'encrassement des surfaces optiques et à la condensation.

17. Mots clés: Capteur à fibres optiques, indicateur de niveau de carburant, mesurage du niveau de carburant d'aéronef.	18. Diffusion: Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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SUMMARY

Fibre optics technology is being increasingly considered by airframe manufacturers for such flight critical systems as primary surface and engine control systems, the so-called fly-by-light concept, as well as for numerous sensor applications. The reasons for this trend include the increasing use of more sophisticated avionics systems which require high bandwidth data buses, the escalating use of composite materials in aircraft which can create an electromagnetic interference (EMI) problem and hence safety problem for electrically operated systems, the normal fibre optic advantages of size and weight reduction, and a desire to interface optical sensors directly to those fibre optic buses which will be present in future aircraft.

The objective of this project was to demonstrate the feasibility of a fibre optic continuous liquid level sensor for aircraft fuel quantity measurement (FQM) leading to a development specification. Such a sensor would offer certain advantages in terms of safety and performance by providing a spark-free, EMI immune and potentially more accurate alternative to conventional capacitance type fuel probes.

Two sensor configurations were developed and tested under this contract. Both resulted from a previously developed generalized configuration based on the principle of total internal reflection which provided an optical signal whose intensity was inversely proportional to liquid level and which provided a superior mechanical assembly to previous sensor schemes. The first configuration employed a fluorescent optical fibre which dictated the optical wavelengths of the light sources and detectors and ultimately poses a major hurdle for its practical application. The second configuration employed rod waveguides fabricated from acrylic with periodic notches along their length to create, in effect, a linear optical source and detector which could be coupled to optical fibres. Both sensor types were optimized through computer models often supplemented by empirical data for key optical elements.

A common lead insensitivity scheme was also developed for both sensors to be able to differentiate the sensor response from other time varying changes in other system components such as lead fibres and connectors. This required duplicate sources and detectors and lead fibres along with some additional electronics, normally present in any FQM system, to perform the ratio calculation.

An automated, instrumented test tank facility was constructed to evaluate the sensors in terms of key performance criteria against a generic FQM specification developed from inputs received from various airframe manufacturers and from relevant

equipment standards. Both sensor configurations demonstrated 5 mm resolution over lengths of 740 mm and 1200 mm for the notched rod and the fluorescent fibre schemes, respectively, as determined by tests in both water and jet fuel. While biological or chemical fouling of the sensors was not observed in over three months of testing, condensation was seen to cause up to a 15 percent error. The fluorescent fibre sensor also suffered from some long term drying effects when drained; this was not seen in the notched rod sensor which demonstrated less than one percent drift over time. For this reason (and because it is intrinsically less sensitive to fouling, provides a linear response, and can be used with inexpensive infrared laser diodes) the notched rod sensor remains the preferred configuration. Both sensors could be implemented at reasonable cost with some tooling investment, e.g. with a sensor parts cost less than $200 and a similar cost for the electro-optic interface.

In terms of the intended FQM application, such a sensor provides a very accurate volume measurement and can be designed to be relatively insensitive to variations in the refractive index of the fuel. In the case of capacitance probes presently in use, these variations lead to an uncertainty requiring compensation normally provided through continuous measurement of the dielectric constant. However, the density and the dielectric constant relationship of the fuel are not constant and the overall system may sustain an error of up to +/- 4%. An actual density measurement or database is needed to convert the volume measurement to the desired mass of fuel remaining and would be more accurate in the case of the optical fibre sensor based on a more precise measure of volume.

The major development uncertainties relate to materials issues; otherwise, development is straightforward. This type of optical application for the coatings, laminations, plastics and other waveguide materials considered is unprecedented. In addition to the basic issues of fabrication and whether the necessary geometries and tolerances can be achieved, other uncertainties include longer term performance in the event of fouling in contaminated fuel, and resolution of the condensation issue through coatings or by other means.

SOMMAIRE

La technologie des fibres optiques prend de plus en plus de place auprès des avionneurs dans la mise au point des principaux systèmes de navigation aérienne dont la gouverne principale et les commandes de moteur - il s'agit de la technologie de commande de vol par fibres optiques - ainsi que dans de nombreuses autres applications faisant appel à des capteurs. Cette tendance s'explique de diverses façons: l'utilisation accrue d'équipement électronique de bord très moderne nécessitant des bus de données à large bande; l'utilisation grandissante de matériaux composites pouvant causer des problèmes d'interférence électromagnétique et par conséquent des problèmes de sécurité pour les systèmes à commande électrique; les avantages qu'offrent les fibres optiques d'être plus légères et plus petites que les autres conducteurs; ainsi que la volonté d'interfacer directement les capteurs optiques aux bus à fibres optiques qui seront utilisés dans les aéronefs de demain.

Ce projet avait pour but de démontrer la faisabilité d'un capteur à fibres optiques pour le contrôle permanent et le mesurage du niveau de carburant (MNC) dans les aéronefs et d'établir les caractéristiques du matériel. Ce type de capteur offre certains avantages relativement à la sécurité et au rendement, car il s'agit d'un dispositif anti-étincelle, à l'épreuve des interférences électromagnétiques et qui constitue un substitut potentiellement plus précis que les indicateurs classiques de mesure de carburant par capacité.

Dans le cadre de ce contrat, les chercheurs ont mis au point et testé deux configurations de capteur. Ces derniers ont été réalisés à partir d'une configuration type déjà existante, basée sur le principe de la réflexion interne globale. Selon ce principe, la réflexion fournit un signal optique dont l'intensité est inversement proportionnelle au niveau du liquide dans lequel la sonde est plongée. De plus cette particularité permet de réaliser un montage mécanique supérieur à ceux des capteurs précédents. Le fonctionnement d'un des capteurs repose sur l'utilisation d'une fibre optique à fluorescence qui demande des longueurs d'ondes précises à la fois aux sources de lumière et aux détecteurs mais qui, en raison de cette contrainte, crée de sérieuses difficultés d'application. Le fonctionnement du second capteur repose sur l'utilisation d'un guide d'ondes ou tige cylindrique en acrylique qui comporte des entailles en des points donnés sur sa longueur dans le but de créer une source optique et un détecteur linéaires pouvant être couplés aux fibres optiques. Le fonctionnement de ces deux capteurs a été optimisé à l'aide de modèles informatiques auxquels des données empiriques ont été souvent greffées pour les principaux éléments optiques.

De plus, les chercheurs ont mis au point un montage insensible à conducteur commun pour que les deux capteurs puissent différencier leurs réponses des autres effets temporalisés du système, notamment la réponse des fibres conductrices et celle des connecteurs. Pour réaliser ce montage, il a fallu doubler les sources de signaux, les détecteurs et les fibres conductrices et ajouter du matériel électronique que l'on retrouve généralement dans tous les systèmes de MNC, pour permettre de faire les calculs requis.

Un réservoir d'essai automatisé et muni des instruments nécessaires a été construit afin d'évaluer les principaux critères de fonctionnement des capteurs en regard des spécifications générales de MNC et établies à partir des renseignements recueillis auprès de différents avionneurs et selon les normes pertinentes. Les essais, menés dans l'eau et le carburéacteur, ont permis de démontrer que les deux types de capteurs ont une résolution respective de 5 mm pour une longueur de 740 mm, dans le montage à tige rainurée, et de 5 mm pour une longueur de 1200 mm dans le montage à fibre à fluorescence. Même si aucun encrassement biologique ou chimique n'a été observé sur les capteurs pendant les quelque trois mois d'essai, les chercheurs ont constaté que la condensation pouvait causer une erreur allant jusqu'à 15 p. 100. A long terme, le capteur à fibre à fluorescence subit les effets de l'assèchement quand le réservoir se vide. Par contre, cet effet n'a pas été noté sur le capteur à tige rainurée puisque sa dérive a été inférieure à 1 p. 100 pour la même période. C'est pourquoi, le capteur à tige rainurée présente la configuration la plus intéressante (sans compter le fait qu'il est essentiellement moins sensible à l'encrassement, qu'il donne une réponse linéaire et qu'il peut être utilisé avec des diodes laser IR peu coûteuses). Les deux types de capteur pourraient être réalisés à prix abordable, en comptant l'achat de certains outils particuliers, c'est-à-dire 200 $ pour les pièces du capteur et un coût similaire pour l'interface électro-optique.

En ce qui à trait à l'application prévue pour le MNC, ce type de capteur permet de faire un mesurage volumique très précis et il peut être conçu de manière à le rendre relativement insensible aux variations de l'indice de réfraction du carburant. Dans le cas des indicateurs par capacité employés présentement, ces variations entraînent une incertitude qui nécessite une compensation de lecture par le mesurage en continu de la constante diélectrique. Cependant, la relation densité-constante diélectrique du carburant peut varier et le système peut comporter une erreur de plus ou moins de 4 p. 100. C'est pourquoi il est nécessaire de recourir à un mesurage réel de la densité ou de faire appel à une base de données pour convertir la mesure volumique en masse de carburant restant. Le résultat de cette opération serait plus exact avec un capteur à fibres optiques, car il serait fondé sur une mesure volumique beaucoup plus précise.

Les principaux problèmes à résoudre concernent les matériaux, car autrement la technologie est assez simple. Ce type d'application des fibres optiques est tout à fait novateur, compte tenu des enduits, lamifiés, plastiques et autres matériaux de guides d'ondes considérés. En plus des problèmes relatifs à la fabrication du matériel, à la géométrie des circuits et au respect des tolérances, il subsiste certaines incertitudes concernant le fonctionnement à long terme du matériel compte tenu du risque d'encrassement d'un capteur immergé dans un carburant contaminé et la possibilité de résoudre le problème de la condensation à l'aide d'enduits ou autres moyens.

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1. INTRODUCTION

1.1 Project Objectives

The objective of this project was to develop and assess an advanced laboratory prototype fuel quantity measurement (FQM) system for primarily aircraft application based on fibre optics technology. It was also intended to prepare a development specification which would conceptually address the various packaging and interface issues for the implementation of the same in the airframe environment.

1.0 Background

Fibre optics technology is being increasingly considered by airframe manufacturers for such flight critical systems as primary surface and engine control systems, the so-called "fly-by-light" concept, as well as for numerous sensor applications. The reasons for this trend include the increasing use of more sophisticated avionics systems which require high bandwidth data buses, the escalating use of composite materials in aircraft which can create an electromagnetic interference (EMI) problem and hence safety problem for electrically operated systems, the normal fibre optic advantages of size and weight reduction, and a desire to interface optical sensors directly to those fibre optic buses which will be present in future aircraft.

The initial concept for a fibre optic FQM sensor stemmed from product development carried out at Focal Technologies Inc. since 1984 in the area of fibre optic sensors for marine and other severe environment applications. The earliest development was a simple point sensor depicted in Figure 1.1 which provided a high or low level indication according to Snell's Law and which addressed the major issue of packaging such a sensor for robustness and maintainability by embedding the optical fibres in a protective window material[1]. Through the introduction of fluorescent optical fibre[2] in the configuration depicted in Figure 1.2, this concept was extended to continuous level sensing thus providing a truly analog output with changing liquid level. The core of the fluorescent optical fibre is doped during manufacture with a

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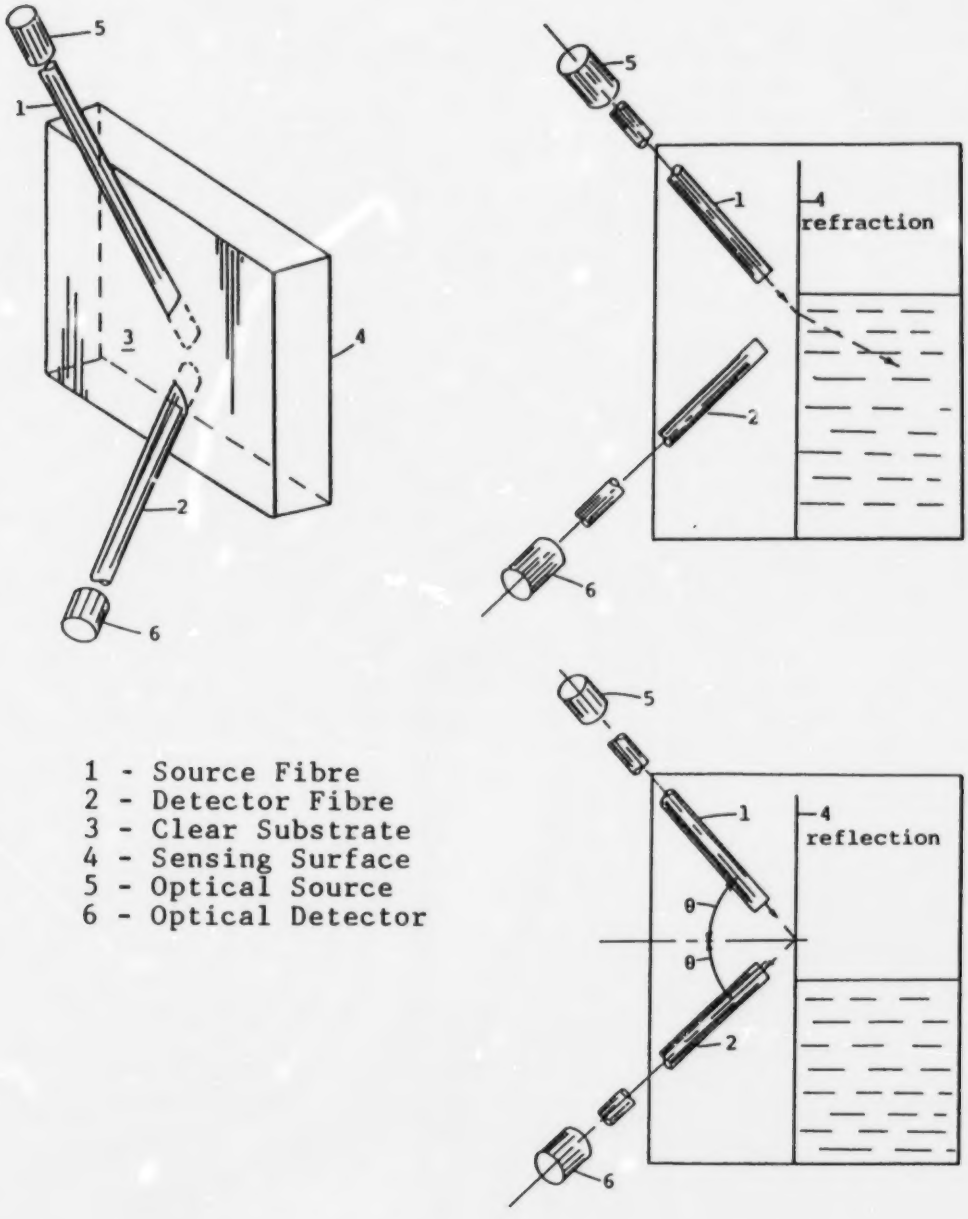
[1] Snow,J.W., "A Fibre Optic Fluid Level Sensor: Practical Considerations", Proceedings of the Society of Photo-Optical Instrumentation Engineers, Vol. 954, Optical Testing and Metrology II, 1988.

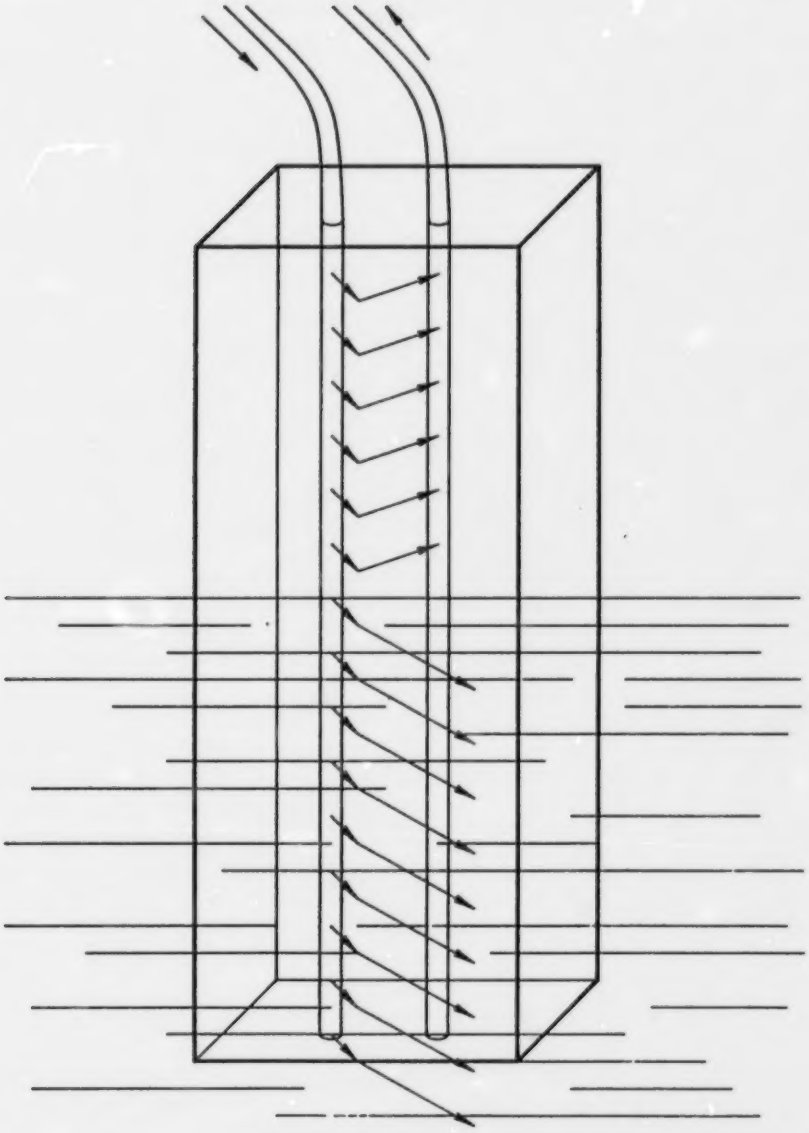
[2] Sawada, H. *et al*, "Plastic optical fibre doped with organic fluorescent material", Proceedings of the Society of Photo-Optical Instrumentation Engineers, Vol. 989, Fibre Optic Systems and Mobile Platforms II, 133-139, 1988.

Figure 1.1 - Fibre Optic Discrete Level Sensor



1 - Source Fibre
2 - Detector Fibre
3 - Clear Substrate
4 - Sensing Surface
5 - Optical Source
6 - Optical Detector

Figure 1.2 - Continuous Level Sensor Concept



fluorescent substance, which when irradiated through the fibre's buffer and cladding with a short wavelength optical source, re-emits light of a longer wavelength. Normally, light passing through an optical fibre in such a manner is not coupled into the waveguide because its angle of incidence exceeds the fibre's numerical aperture or acceptance cone for longitudinal propagation (Figure 1.3). However, a portion of the light which is emitted from the fluorescent centres will remain as guided light in the fibre's core and will propagate to both ends of the fibre. By embedding such a fluorescent fibre in a suitable optical substrate material along with another optical fibre which was abraded along its length to create a line source of light, it was experimentally shown to be possible to sense a liquid level change inversely proportional to the received fluorescent light intensity. The initial sensor which was constructed in 1987 was very crude and optical power level changes of 5 dB were measured over a sensor length of only 2 cm.

Such a sensor for aircraft FQM was seen to offer certain advantages in terms of safety and performance by providing a spark-free, EMI immune and potentially more accurate alternative to conventional capacitance type fuel probes. Encouragement was also received from Boeing, McDonnell-Douglas, and Canadair in pursuing such a scheme. Both Boeing and McDonnell-Douglas have for some time been pioneering the introduction of fibre optics technology into various airframes and have active research and development programs in this area[3].

1.3 Method

The 1987 prototype referred to above was far from optimum in its design and performance. The abraded fibre line source emitted light at predominately very shallow angles, not radially as desired, and had a broad angular emission pattern rather than a focused one. The fluorescent fibre available at that time was only excited at very short wavelengths in the ultraviolet to blue portion of the spectrum and fluoresced in the green well below the infrared wavelengths required for efficient fibre optic implementation.

Consequently, a generalized sensor configuration was developed as depicted in Figure 1.4. Each of its key optical elements were reviewed towards defining and specifying a refined prototype. At the same time, airframe manufacturers were consulted for information on their FQM requirements towards

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[3] Todd,J.R., "Development of Fly-By-Light Systems", Proceedings of the Society of Photo-Optical Instrumentation Engineers, Vol. 1173, Fibre Optic Systems for Mobile Platforms III, 1989.

Figure 1.3 - Fluorescent Fibre

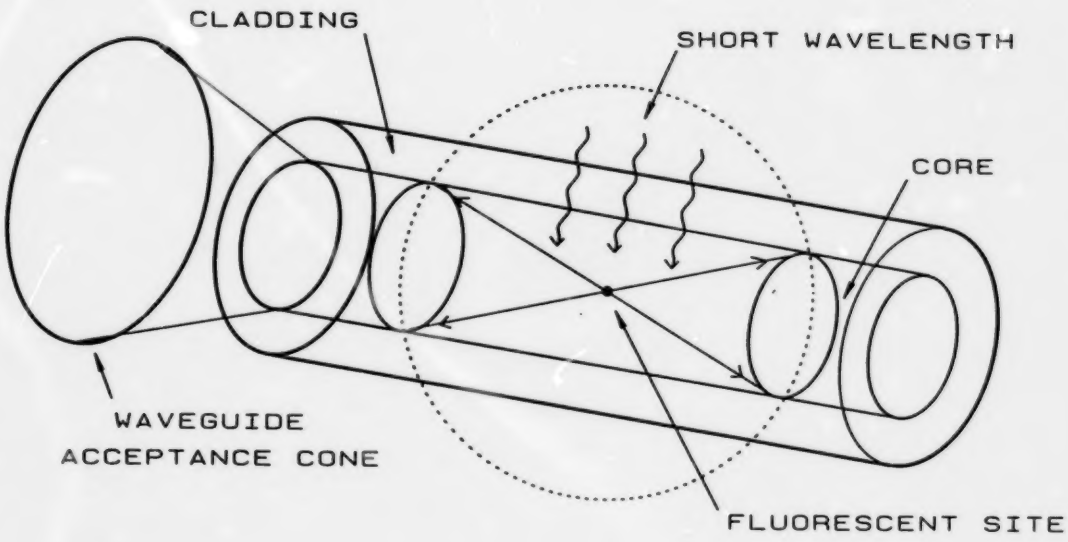
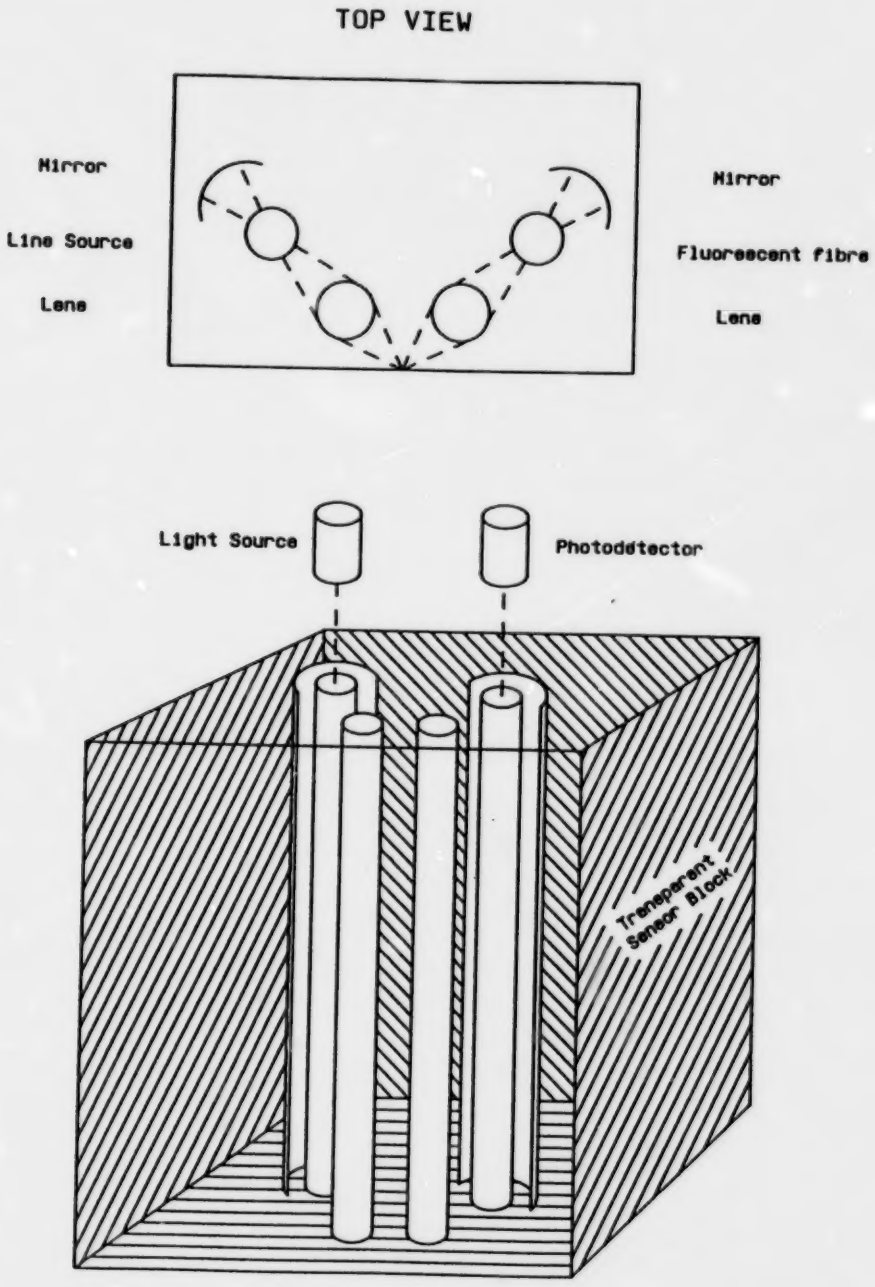


Figure 1.4 - Generalized Continuous Level Sensor Configuration



the development of a generic FQM specification which could be used as the basis for evaluation in this study.

Optical fuel gauge prototypes were then designed per the derived specifications, constructed, and tested for both basic optical performance and in terms of the airframe environment leading to conclusions on the suitability of such as sensor for the chosen application and the identification of key development requirements.

Detailed review of the results of these tasks is covered in the following sections.

2. SYSTEM REQUIREMENTS

The following is a summary of specifications and requirements for aircraft fuel quantity measurement systems which were used to evaluate the prototype optical fuel gauges. The composite "generic" specification provided a representative intersection set for this project (Tables 2.1 and 2.2). The information was drawn primarily from the following specification documents supplied by Canadair, Boeing, and McDonnell-Douglas through proprietary data agreements:

Canadair - CES-730 "FUEL QUANTITY GAUGING SYSTEM"

Boeing - S345T002 "757/767 FUEL QUANTITY INDICATING SYSTEM SPECIFICATION CONTROL DRAWING"

McDonnell-Douglas
- C1-E00-88-003810 letter dated 14 June 1988

The following documents were also examined:

MIL-STD-810B METHODS	"MILITARY STANDARD ENVIRONMENTAL TEST AND ENGINEERING GUIDELINES"
MIL-T-5624L	"MILITARY SPECIFICATION TURBINE FUEL, AVIATION, GRADES JP-4 AND JP-5"
RTCA/DO-160B PROCEDURES	"ENVIRONMENTAL CONDITIONS AND TEST FOR AIRBORNE EQUIPMENT"
MIL-C-45662	"CALIBRATION SYSTEM REQUIREMENTS"
MIL-F-8615	"FUEL SYSTEMS COMPONENTS, GENERAL SPECIFICATION FOR"
MIL-G-5572	"GASOLINE, GRADES 80/87, 100/130, 115/145"
MIL-G-26988 FOR"	"GAGE, LIQUID QUANTITY, CAPACITOR TYPE, TRANSISTORIZED, GENERAL SPECIFICATION
MIL-I-25017	"INHIBITOR, CORROSION, FUEL SOLUBLE"
MIL-I-27686	"INHIBITOR, ICING, FUEL SYSTEM"
MIL-STD-210	"CLIMATIC EXTREMES FOR MILITARY EQUIPMENT"
MIL-STD-454 ELECTRONIC	"STANDARD GENERAL REQUIREMENTS FOR EQUIPMENT"
MIL-STD-704 CHARACTERISTICS	"ELECTRICAL POWER, AIRCRAFT, AND UTILIZATION OF"

MIL-T-38219 "TURBINE FUEL, LOW VOLATILITY, JP-7"

MIL-T-83133 "TURBINE FUEL, AVIATION, KEROSENE TYPE, GRADE JP-8"

The maximum allowable error quoted is for the overall system, ie. the accuracy of measurement and processing in determining the weight of fuel in a given tank. Accuracy is quoted for cruise conditions in the case of Canadair and for all craft attitudes between 0 - +/-20 degree pitch and 0 - +/-5 degree roll for Boeing. McDonnell-Douglas states that the sensor resolution must be better than 1%.

Although Boeing does not specify a sensor diameter, representative numbers (1.5, 2.5 inch i.d.) are given for the bulkhead receptacle diameter (through which pass the electrical connections of a capacitive type sensor).

Boeing has a weight control policy rather than a weight limitation : "The weight of the article shall be a minimum consistent with the stated design requirements and within the limitations of sound design practices." (Boeing Specification Control Drawing S345T002 paragraph 3.1.2).

The environmental requirements of the signal processing unit are generally different from that of the sensor because of the location. Presumably the electronics bay resides somewhere in the fuselage while the main fuel tanks are in the wings.

Electrical power supplied at 28 V dc seems standard, and reference is made (Boeing) to 400 Hz ac of unspecified voltage.

TABLE 1 - FUEL PROBE SPECIFICATIONS

	Canadair Challenger	Boeing 757 / 767	McDonnell-Douglas	Generic
Max. error	1% full scale + 1% actual	5% of full scale	1% of full scale	1% of full scale + 1% actual
Sensor length	18 inches	up to 55.58 inches	up to 60 inches	1 metre
Sensor diameter	< 1.12 inches	not specified	not specified	< 2.8 cm
Sensor weight	< 8.5 lb	not specified	not specified	0.18 kg/cm
Sensors/tank	not specified	not specified	3 to 15	not specified
Sensor coating	not specified	polyurethane	polyurethane	not specified
ENVIRONMENTAL				
Temperature	-65 to 70 C	-51 to 71 C	-61 to 74 C	-65 to 70 C
Temp. shock	not specified	MIL-STD-810	42 C / minute	42 C / minute
Pressure (alt.)	-1000 to 50,000 feet	not specified	-1800 to 50,000 feet	-1000 to 50,000 feet
Pressure (abs.)	50 inches Hg	-57.2 kPa	not specified	50 inches Hg
Humidity	95% R.H.	95% R.H.	100% R.H.	95 % R.H.
Shock	RTCA DO160 Sec. 7	MIL-STD-810	MIL-STD-810, method 516.2	RTCADO160 Sec. 7
Vibration	MIL-STD-810	MIL-STD-810	RTCA DO-160	MIL-STD-810
Acceleration	10 g	12 g	8.8 g	10 g
RELIABILITY				
Overall system	CES-600	MTBF 15,000 hours	30 years	20 years
Component	-	MTBF 250,000 hours	-	not specified
Service life	-	60,000 hours	30,000 hours	not specified
FUEL TYPE				
Primary	Jet-A, Jet-A1, Jet-B, JP4, JP5	JP-4, JP-5, JP-8	JP4, JP8	All fuel types
Alternate	-	Gasoline, grades 80/87, 100/130, 115/145	Jet A, Jet A-1, Jet B JP5, JP7, Av. gas.	

TABLE 2.2 - SIGNAL PROCESSING UNIT SPECIFICATION

	Canadair Challenger	Boeing 757 / 767	McDonnell-Douglas	Generic
Weight	< 2 lb	not specified	not specified	< 1 kg
Dimensions	< 5.57 X 4.09 X 3.40 inches	not specified	not specified	< 14 X 10 X 8 cm
ENVIRONMENTAL				
Temperature	-30 to 50 C	-51 to 71 C	-61 to 74 C	-30 to 50 C
Temp. shock	not specified	MIL-STD-810	42 C / minute	42 C / minute
Pressure (alt.)	-1000 to 50,000 feet	not specified	-1800 to 50,000 feet	-1000 to 50,000 feet
Pressure (abs.)	50 inches Hg	-57.2 kPa	not specified	50 inches \hg
Humidity	95% R.H.	95% R.H.	100% R.H.	95 % R.H.
Shock	RTCA DO160 Sec. 7	MIL-STD-810	MIL-STD-810, method 516.2	RTCA DO160 Sec. 7
Vibration	MIL-STD-810	MIL-STD-810 Zone 2, Fig 4.1, Category A	RTCA DO-160	MIL-STD-810
Acceleration	5 g	9 g	4.35 g	5 g
ELECTRICAL				
Input voltage	28 V dc	28 V dc	DAC WZZ7364	28 V dc
Input power	10 W	not	DAC WZZ7364	10 W
Signal scaling	5 V = 5400 lb	not specified	not specified	not specified
Output impedance	2 k ohm	not specified	not specified	2 k ohm
Insulation resist.	20 M ohm	20 M ohm	MIL-STD-454	20 M ohm
Dielectric strength	140 V rms	1500 V ac	DAC WZZ7364	140 V rms
Wiring length	not specified	up to 200 ft	not specified	not specified
Lightning transient immunity protection	not specified	"shall incorporate protection devices"	DAC BXU7026 category A	must incorporate
RELIABILITY	CES-600	17,000 hour MTBF	not specified	20 years

TABLE 2.3 - FUEL ADDITIVES

Canadair

Anti-icing	: ethylene glycol monomethyl ether (EGME) 0.1 to 0.15 % by volume
Static dissipator	: ASA-3 (Shell) ; STADIS 450 (Dupont petroleum)
Oxidation inhibitor	: 4 types
Metal deactivator	: 5.7 mg/l nn Disalicylidene 1,2 ; propane diamine

McDonnell-Douglas

Biocide	: BIOBOR, up to 270 ppm (20 ppm elemental)
Corrosion inhibitor	: HITEC E-515, up to 16 #/1000 bbl
Icing inhibitor	: FUEL SYSTEM ICING INHIBITOR, up to 0.15 % by volume
Conductivity improver	: ASA-3, up to 1 ppm
Corrosion inhibitor	: TOLAD 245, up to 20 #/1000 bbl
Conductivity improver	: STADIS 450, up to 3 ppm
	: NALCO -5403, up to 8 #/1000 bbl
	: DUPONT DCI-4A, up to 8 #/1000 bbl

Boeing

not specified

Generic

Anti-icing	: ethylene glycol monomethyl ether (EGME) 0.1 to 0.15 % by volume
Static dissipator	: ASA-3 (Shell) STADIS 450 (Dupont petroleum)
Oxidation inhibitor	: 4 types
Metal deactivator	: 5.7 mg/l nn Disalicylidene 1,2 propane diamine
Biocide	: BIOBOR, up to 270 ppm (20 ppm elemental)
Corrosion inhibitor	: HITEC E-515, up to 16 #/1000 bbl
Icing inhibitor	: FUEL SYSTEM ICING INHIBITOR, up to 0.15 % by volume
Conductivity improver	: ASA-3, up to 1 ppm
Corrosion inhibitor	: TOLAD 245, up to 20 #/1000 bbl
Conductivity improver	: STADIS 450, up to 3 ppm
	: NALCO -5403, up to 8 #/1000 bbl
	: DUPONT DCI-4A, up to 8 #/1000 bbl

The only reference to potential fouling in those documents examined was in regard to fungus resistance. The following from MIL-STD-810B Method 508.3 describes the effect of excessive fungal growth :

Detrimental Effects

i) Direct attack on materials:

Nonresistant materials are susceptible to direct attack as the fungi break the material down and use it as food. This results in deterioration affecting the physical properties of the material.

ii) Indirect attack on materials:

Damage to fungus resistant materials results from indirect attack when :

1) fungal growth on surface deposits of contaminants causes damage to the underlying material even though that material may be resistant to attack.

2) metabolic waste products (ie. organic acids) excreted by fungi cause corrosion of metals, etching of glass, or staining or degrading of plastics or other materials.

3) the products of fungal growth on adjacent materials which are susceptible to direct attack come in contact with resistant materials.

Physical Interference - Optical Systems

Damage to optical systems results primarily from indirect attack. The fungal growth can adversely affect light transmission through the optical system, block delicate moving parts, and change non-wetting surfaces to wetting surfaces with resulting lack of performance.

Recommended Test Cultures

Canadair and Boeing each list the following representative types for evaluating the fungal resistance of materials:

1) Aspergillus niger
2) Aspergillus flavus
3) Aspergillus versicolor
4) Penicillium funiculsum
5) Chaetomium globosum

In addition, Seatech Investigations Services (Halifax N.S.) warns of a widespread microbiological contamination in fuel tanks by the "kerosene fungus" Cladosporium resinae.

6) Cladosporium resinae

McDonnell-Douglas requires that all tank components have an anti-fungi additive in their coating compound which will inhibit the growth of micro-organisms that thrive in water-contaminated fuels.

The fuel additives noted in Table 2.3 must also be considered with regard to the chemical resistance of the selected materials.

3. SENSOR CONFIGURATIONS

3.1 Introduction

Over the course of the fibre optic fuel gauge development, several sensor configurations were considered. Figure 3.1 depicts in flowchart form the configurations which were assessed and resulted from the generic scheme depicted in Figure 1.4.

The earliest approaches to continuous liquid level sensing employed a "line source", i.e. an optical source which emits light distributed along a line. Initial line sources were created by abrading a plastic optical fibre by filing, by polishing or by nicking with a knife edge. This approach was motivated by a desire to be able to connect the line source directly to the optical light source through an intervening lead fibre without the need for lenses or other inefficient coupling schemes. Several experiments were conducted on the abraded fibres to gauge the effectiveness as a line source through the following measurements:

- the intensity distribution along the abraded length of the fibre (Figure 3.2)
- the aperture of the abraded fibre (Figure 3.3)
- the exit angle with respect to the fibre axis (Figure 3.4)

Figure 3.5 explains the nomenclature used.

The fibres demonstrated an approximately exponential decrease in light intensity along their length (typically 25 dB/m) that was not very uniform. The aperture measurement showed that approximately equal portions of light exit the front and the back of the fibre and that there was only partial concentration in the preferred direction. The light which was stripped from the fibre was also seen to do so at predominately shallow exit angles not at 90 degrees as desired. Consequently this approach was abandoned for reasons of poor performance and difficulties in fabrication. A lensed array solution (Figure 3.6) was also abandoned for similar reasons.

However, out of these apparent failures, two configurations resulted which were demonstrated to be capable of sensing liquid level changes over 1-2 metres:

3.2 Notched Rod Sensor

An alternative to the abraded fibre line source is shown in Figure 3.7. In this notched rod configuration, the waveguide perturbations are smooth notches which act as specular mirrors rather than diffuse scattering sites associated with the

Figure 3.1 - Configuration Development Flow Chart

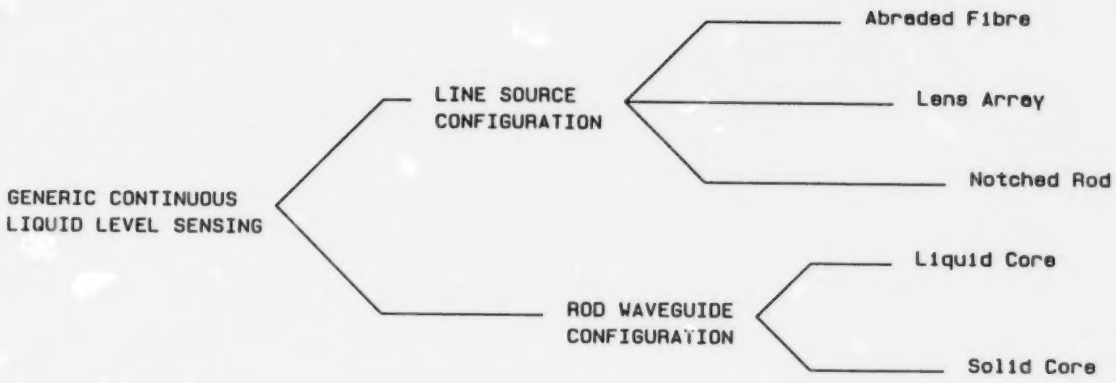


Figure 3.2 - Intensity Distribution Along An Abraded Fibre

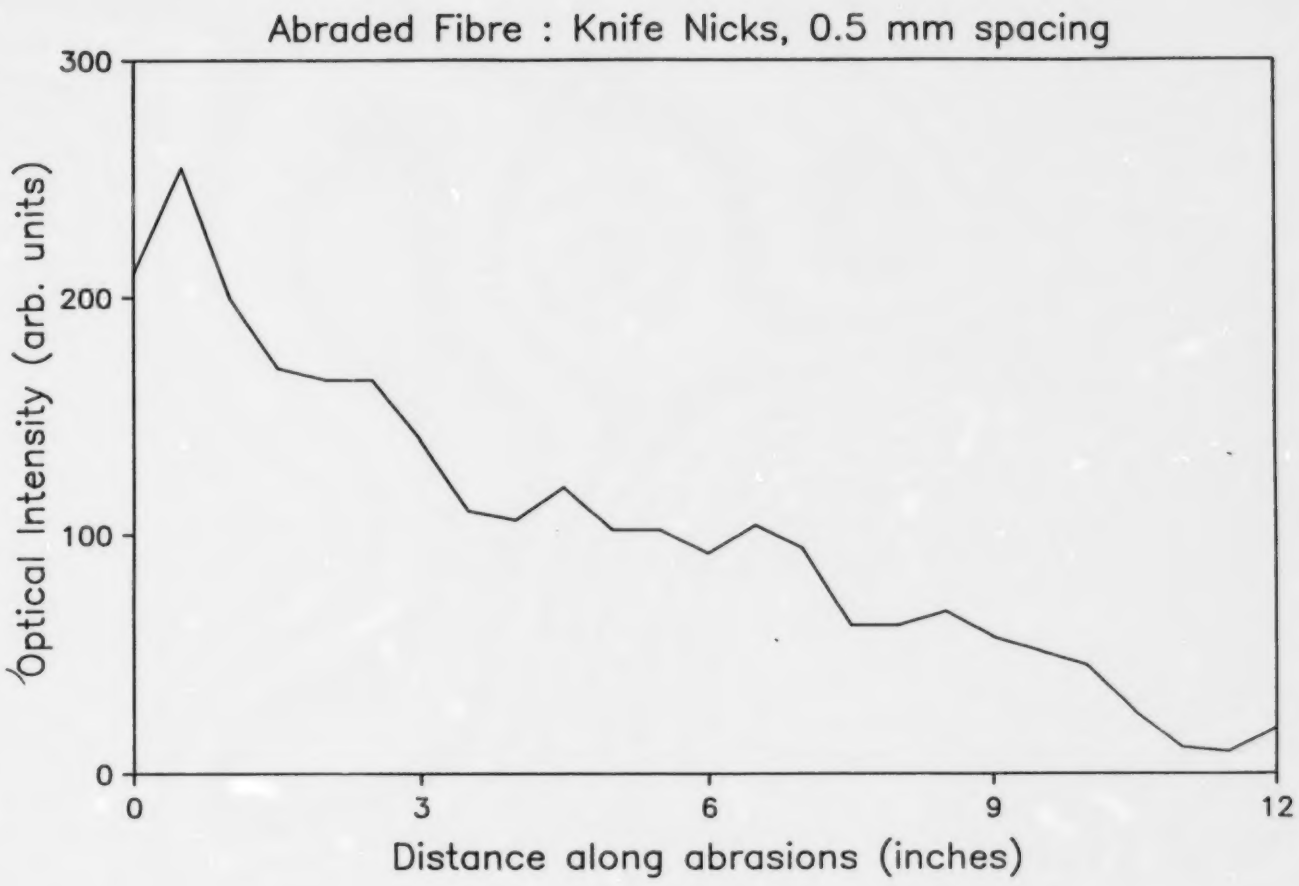


Figure 3.3 - Emission Aperture Of An Abraded Fibre

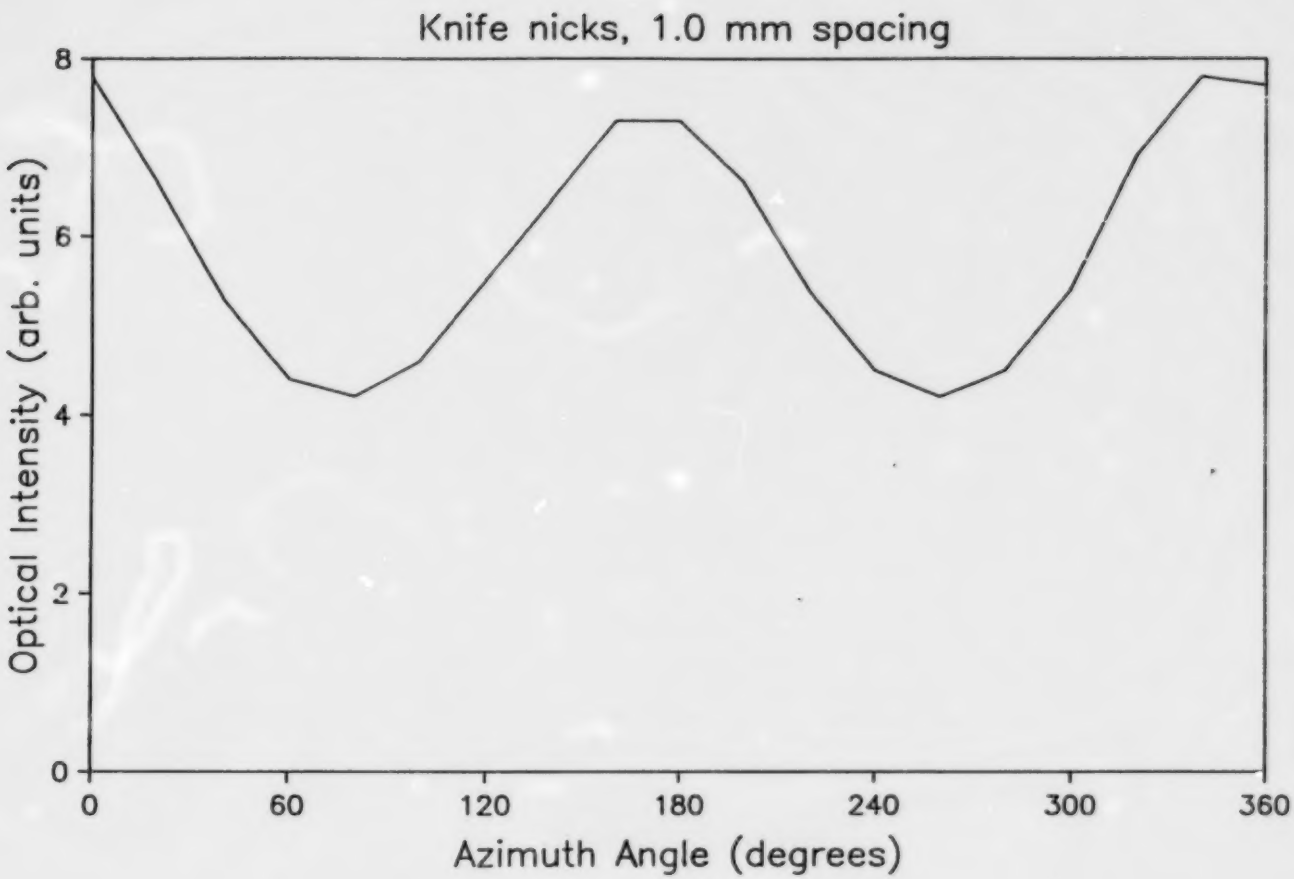


Figure 3.4 - Exit Angle With Respect to Fibre Axis

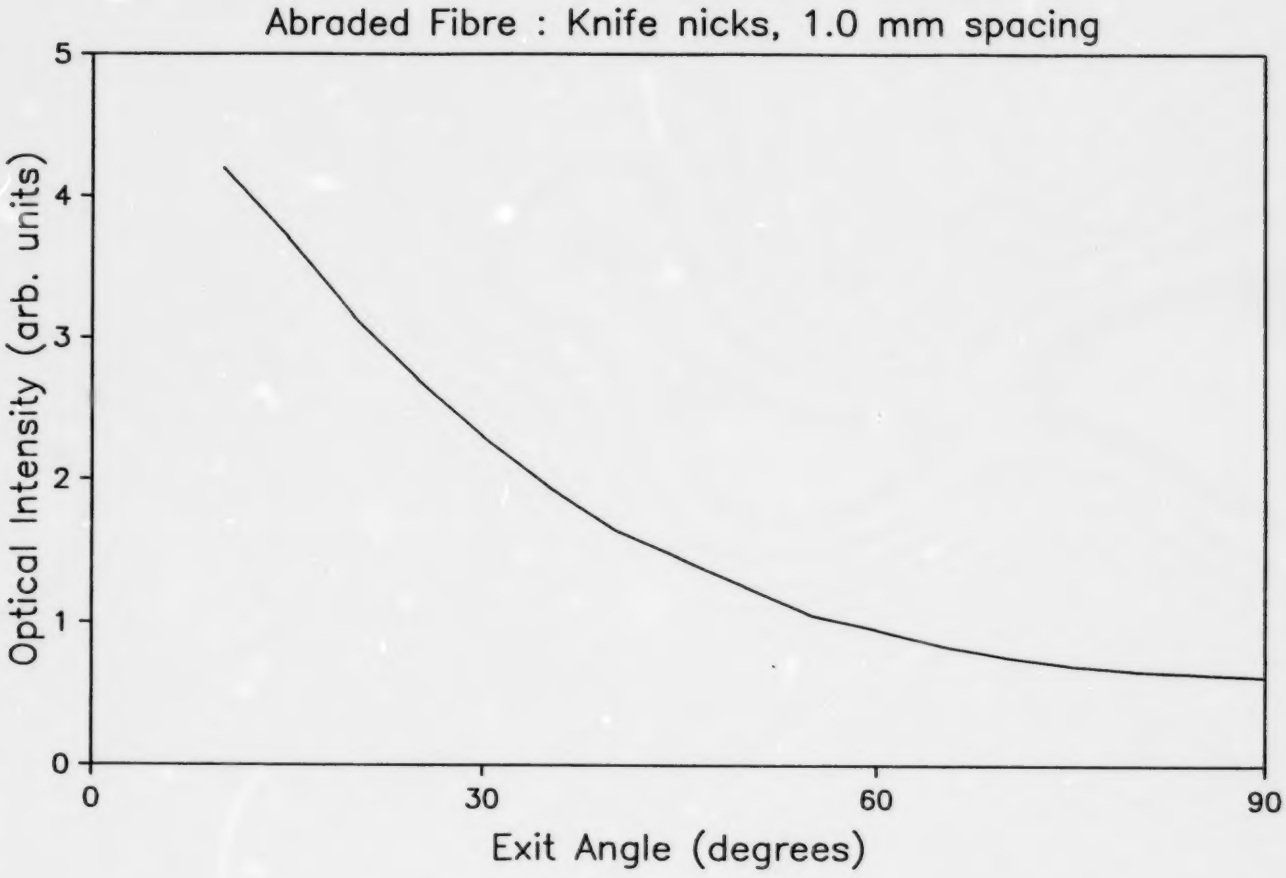


Figure 3.5 - Abraded Fibre Nomenclature

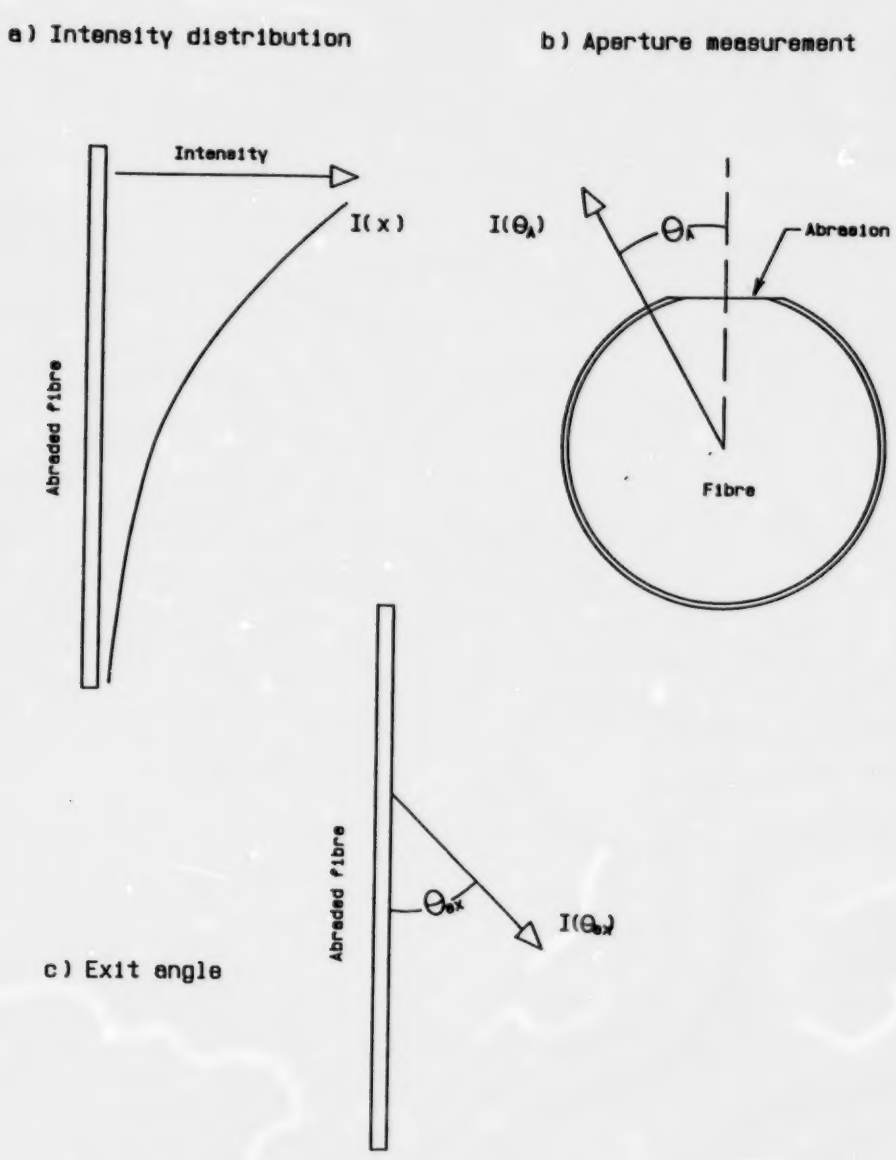


Figure 3.6 - Lens Array Line Source

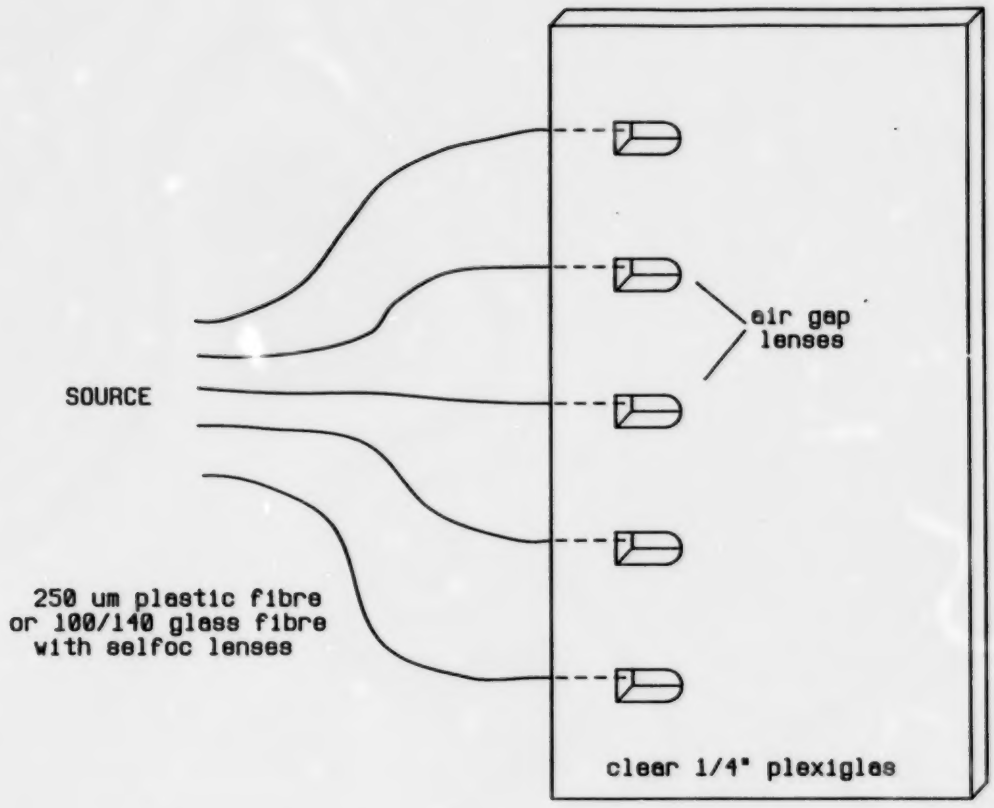
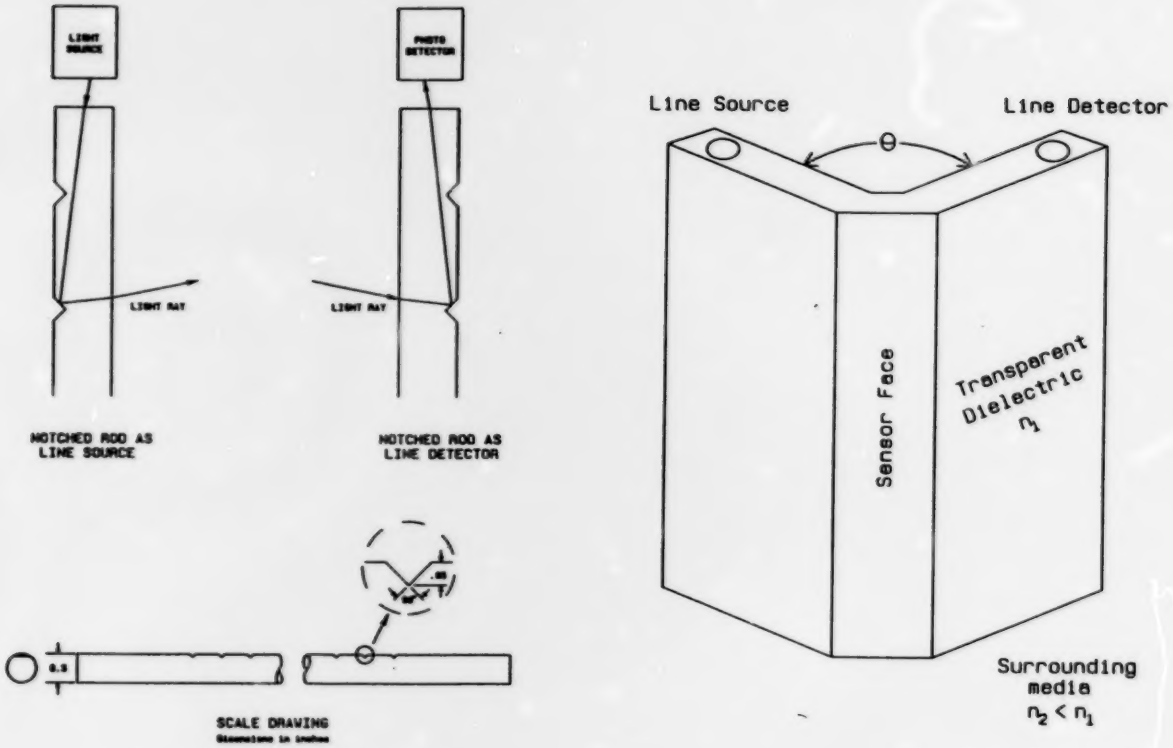


Figure 3.7 - Notched Rod Concept



abrasion techniques. By varying the notch depth and spacing for a given rod diameter, a uniform, highly directional, radial line source is created (Figures 3.8 and 3.9). A particularly interesting feature of this scheme is that it is bidirectional, i.e. the rod may be used both as a line source and as a line receptor, eliminating the requirement for the fluorescent fibre, which means that more conventional infrared sources for fibre optic application may be used.

Two 74 cm notched rod sensors were constructed and tested after some initial experimentation and computer modelling to determine the optimum notch spacing and depth for a given diameter rod.

An isometric view of the actual sensor implementation is given in Figure 3.10. The sensors were made entirely of clear acrylic, except for a black acrylic divider used to prevent light from being coupled directly from one notched rod to the other. The V-waveguide was constructed from two 0.3 x 3 x 74 cm pieces of acrylic, each with one of its long edges faced at 55 degrees. The other long edges were polished using 0.3 micron polishing compound and a buffing wheel. Once polished, these pieces were solvent welded to the front of the acrylic box with methylene chloride to form the "V".

The notched rods were 0.64 cm in diameter, with the 0.33 mm deep notches uniformly spaced at 0.64 cm. They were held in place at each end by an O-ring within an acrylic holder which was welded to the V-waveguide, and in the middle by another acrylic holder.

Four 1 mm plastic lead fibres were potted with a clear epoxy on the end of the notched rods, two at the top of one rod and two at the bottom of the other. The six sheets of acrylic which formed the outer box were also solvent welded, and any remaining gaps were filled with a clear epoxy. The lid of the probe was penetrated by two acrylic tubes, which were used to suspend the sensor in the test tank and through which the lead fibres were routed. The lead fibres had polished ends which could be either connected to a laser diode source or butt coupled in a temporary acrylic splice to a pigtailed high efficiency red light emitting diode (LED).

Construction of the second notched rod probe was similar to that of the first. A commercial solution for solvent welding was used instead of methylene chloride, and the technique was improved such that the acrylic sections fitted better and remained stationary while curing. As a result the welds creating the V-waveguide appeared as a continuous piece of acrylic, exhibiting almost no voids or irregularities. Since the welds which formed the enclosure mated well also, there was no need to apply epoxy to fill gaps. An extrusion would be the long term solution. As an extra guarantee against jet

Figure 3.8 - Notched Rod Aperture

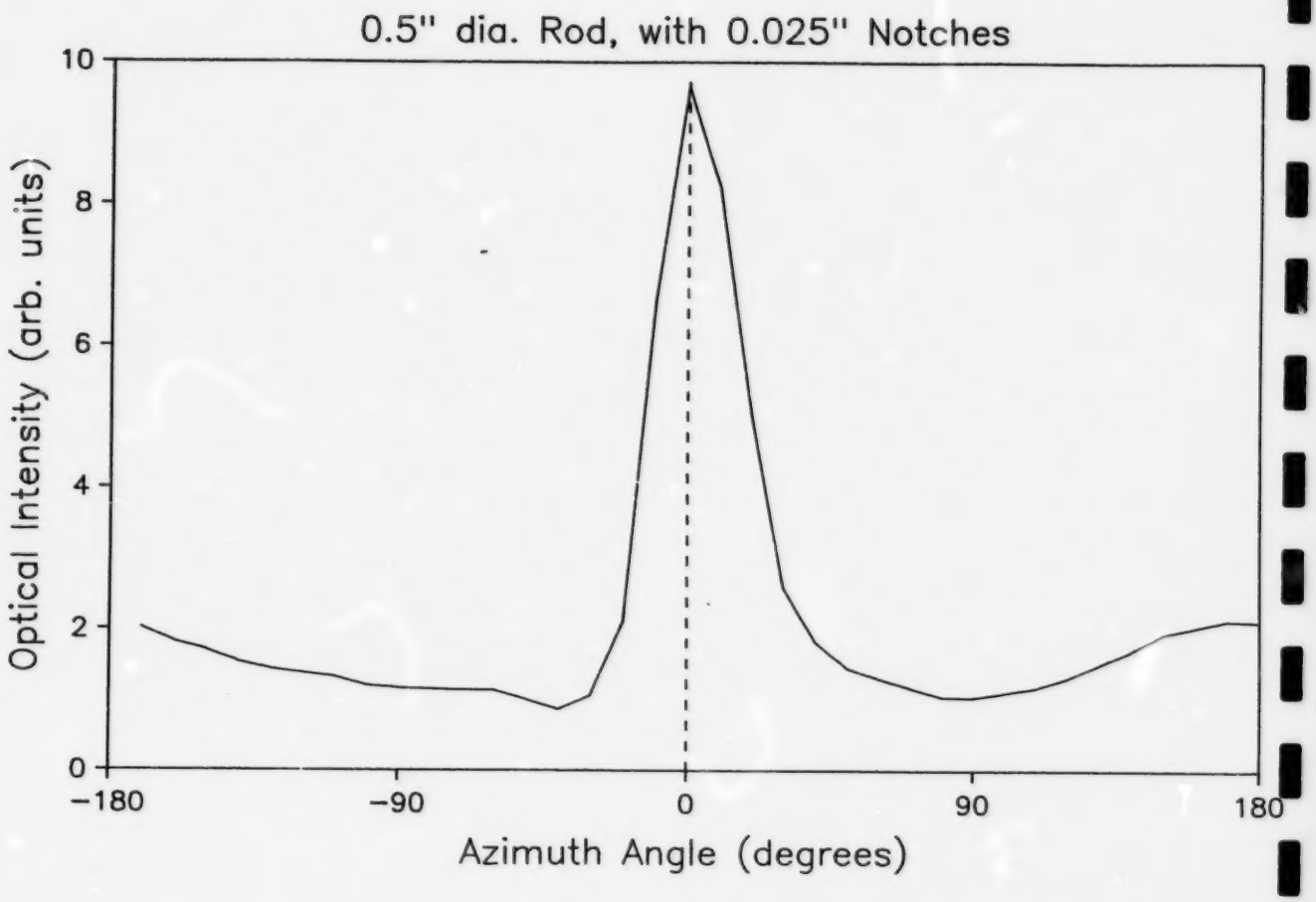


Figure 3.9 - Exit Angle From Notched Rod

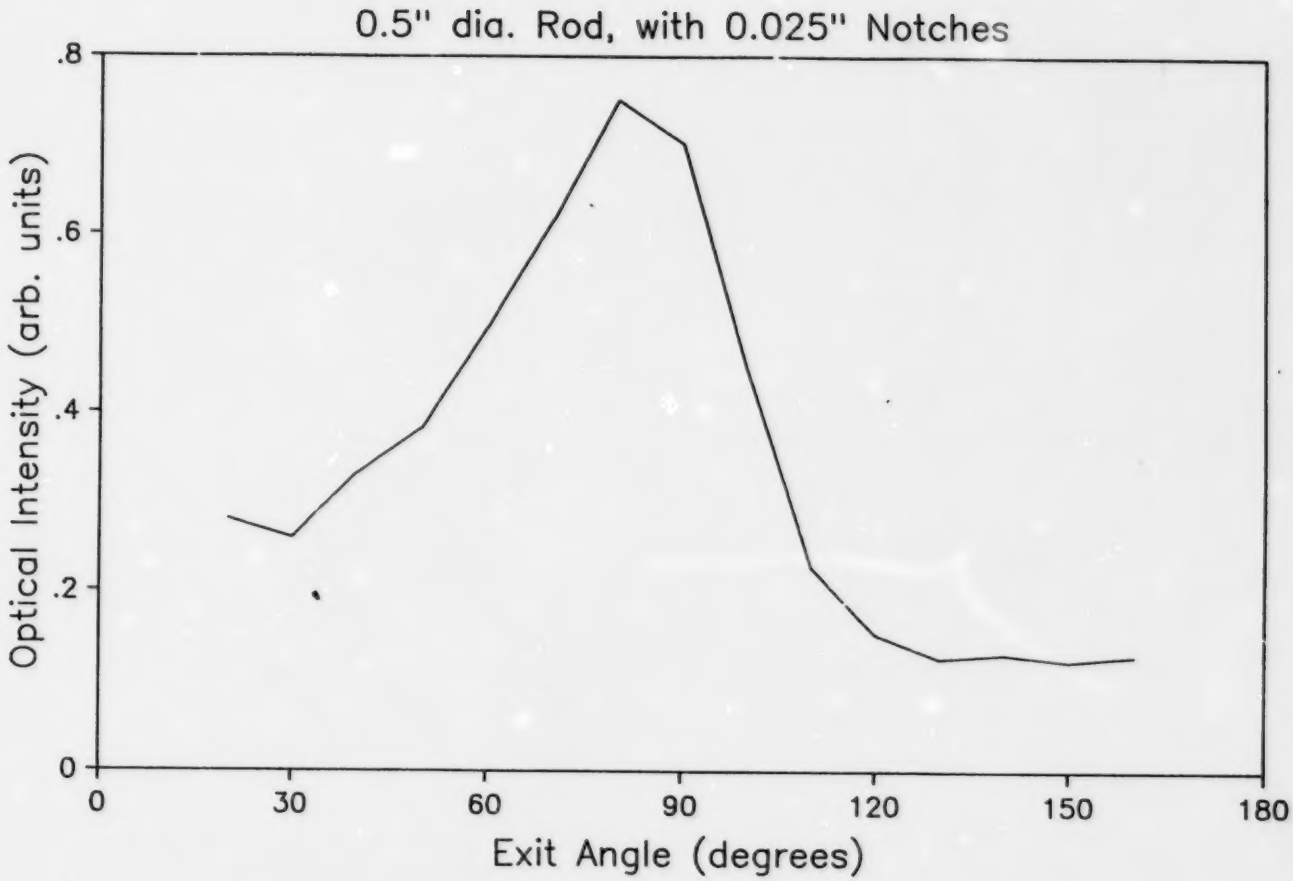
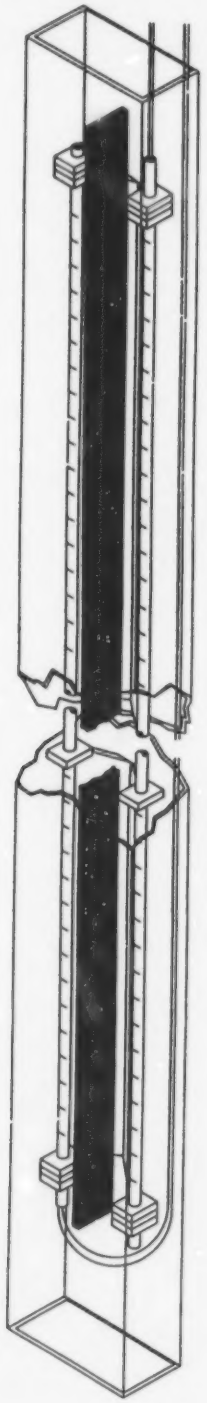


Figure 3.10 - Isometric View Of Assembled Notched Rod Sensor



fuel penetration, a general purpose hydrocarbon resistant sealant was applied to all outer seams of this probe.

3.3 Rod Waveguide Sensor

A much simpler geometry for a TIR fluorescent fibre sensor is depicted in figure 3.11. In this configuration the light from the source fibre is launched into the waveguide (acrylic rod) at a high angle. Because of the high numerical aperture of the light exiting the fibre, the light fills the waveguide after several internal reflections. As the liquid level rises the light is refracted out yielding a fluorescent signal which is inversely proportional to level.

As for the notched rod sensor, ray tracing analysis was used to supplement experiment in determining the optimum design (Figure 3.12). The experiments in this case included the construction of very crude sensors from stoppered glass tubes filled with glycerin in which the fluorescent fibre and the source fibre were inserted.

Two 120 cm solid fluorescent rod waveguide probes were constructed. The first was constructed from 0.5 inch clear cast acrylic rod with a machined longitudinal groove. A 1 mm diameter "red" fluorescent fibre (ie. absorbs green light and emits red) was potted in the groove using a clear epoxy. Four 0.5 mm plastic fibres pigtailed to high efficiency green light emitting diodes injected the pump light at the top of the acrylic rod. The reference signal was generated by illuminating a portion of the fluorescent fibre above the acrylic rod with a 1 mm plastic fibre / green LED pair. Each end of the fluorescent fibre was butted to a 1 mm plastic detector fibre. The acrylic rod was coupled on top to an acrylic tube and on bottom to a copper "U" fitting and pipe through which the lead fibres were routed.

The construction of the second rod waveguide prototype was similar to that described above, but this time a 0.75 inch acrylic rod was used. All optical leads were changed to 1 mm plastic fibres, and higher power light emitting diodes were substituted. Two 1 mm fibres were used to inject light for the reference signals to further improve the optical power levels.

3.4 Lead Insensitivity

Intensity type optical sensors are those in which the detected optical intensity indicates the measured quantity. Intensity type sensors are also sensitive to changes in source intensity, detector responsivity, and attenuation in the optical fibres and connectors leading to and from the sensor. It is impossible to directly differentiate between one of the changes listed and a real change of the measured quantity.

Figure 3.11 - Fluorescent Fibre / Rod Waveguide Sensor

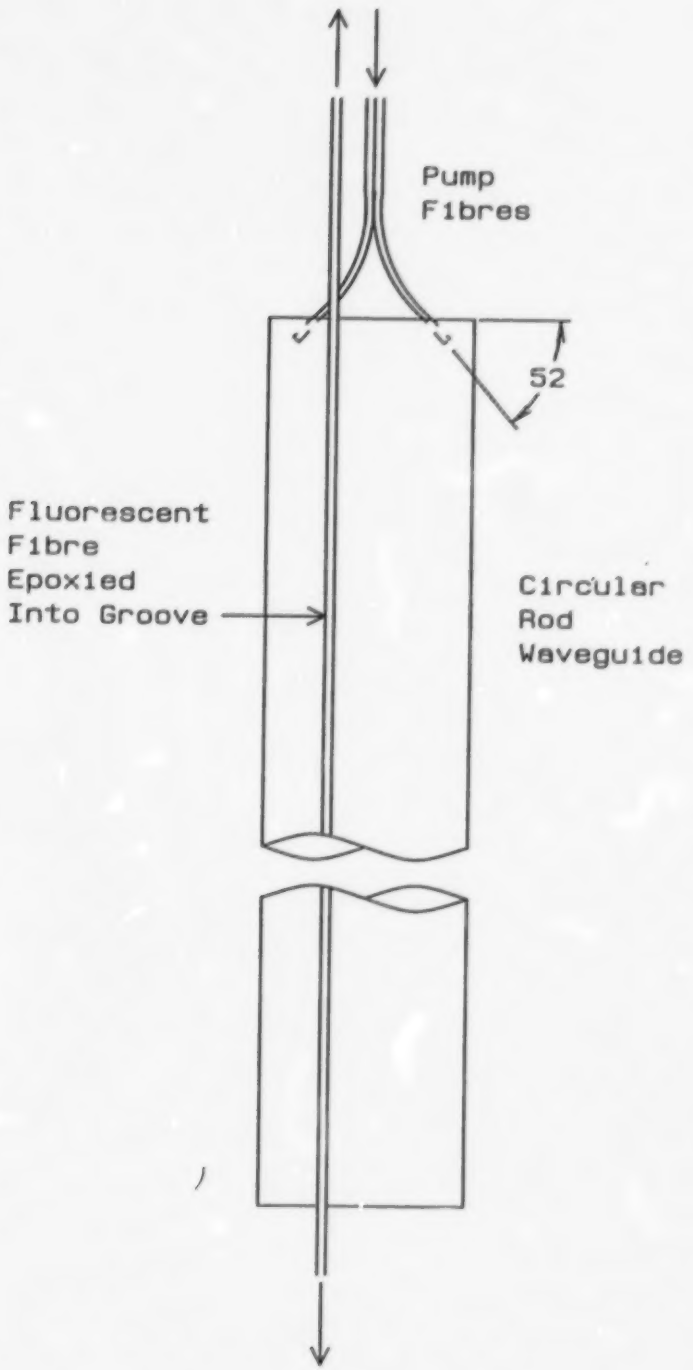
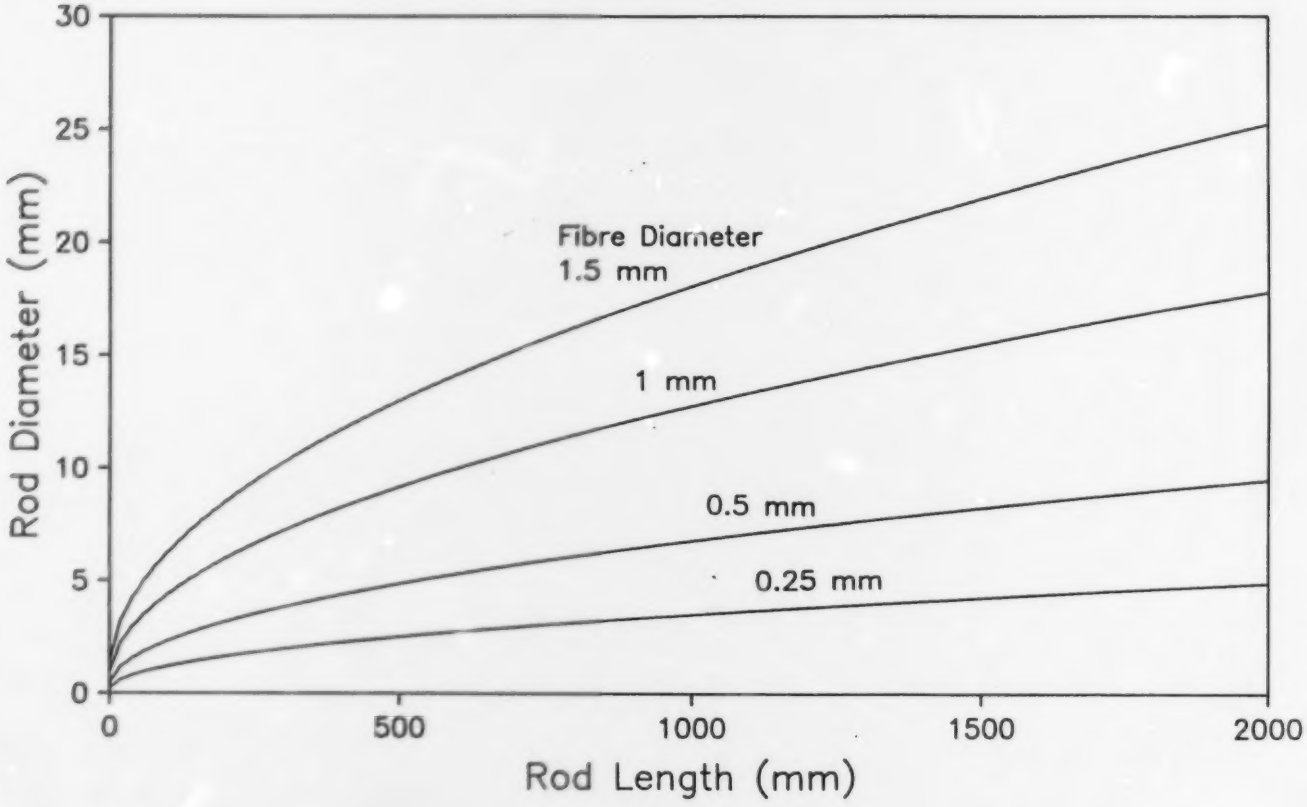


Figure 3.12 - Rod Waveguide Design Curves



The rod waveguide type fuel probe and the notched rod type fuel probe are intensity-type sensors, since the intensity of the detected signal indicates the fuel level. However, variations in lead fibre and connector attenuation as well as source and detector changes must be accommodated by the sensor in this application. Special techniques must be employed to eliminate sensitivity to lead fibre attenuation.

The literature contains such techniques for the reduction of lead fibre sensitivity as multiple pass pulses, wavelength referencing, polarization, Doppler, few mode, and reference path techniques. Of these, only wavelength referencing is applicable to the optical fuel probes but require wavelength sensitive couplers and multiwavelength sources, a particular problem for the fluorescent fibre schemes. A simpler reflection/transmission technique using two light sources and two detectors has recently been reported by Beheim and Anthan[4]. This technique has been modified for use with the rod waveguide fuel probe and also for the notched rod fuel probe, as described in the following sections.

3.4.1 Rod Waveguide Lead Insensitivity

In this method, two outputs are required which have different intensity versus fuel level responses. For the rod waveguide type probe, suitable outputs are the top and bottom ends of the fluorescent fibre. These two outputs behave differently because of the self-attenuation of the fluorescent fibre. In addition, two inputs are required which cause different responses at the outputs. One input can be the normal source fibre. The second input can be a fibre simply butted against the fluorescent fibre outside the fuel-sensing portion of the probe. The resulting configuration is shown in Figure 3.13.

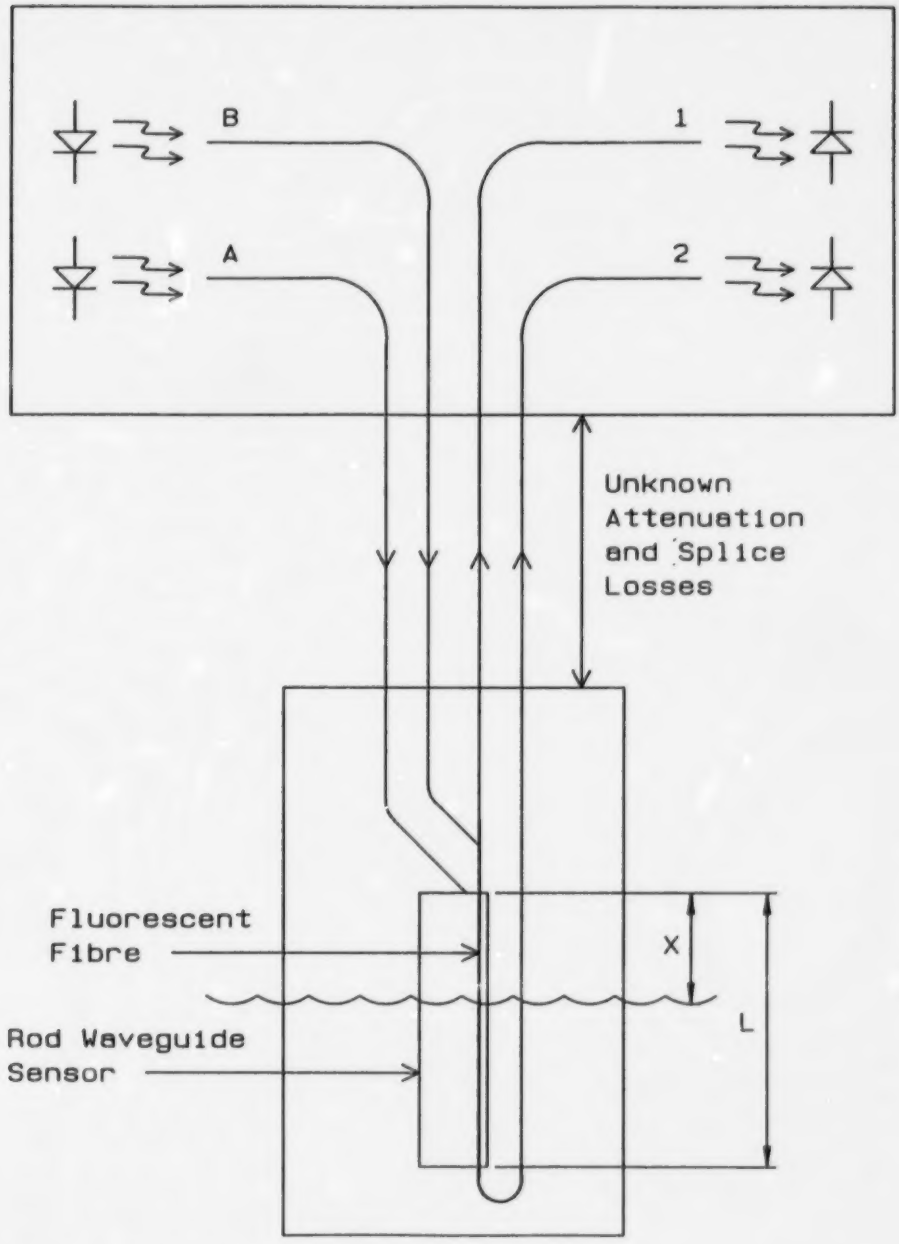
To take a level measurement, LED B only is turned on, and P_{1B} and P_{2B}, the optical powers at detectors 1 and 2, respectively, are measured. Then LED B is turned off, LED A is turned on and P_{1A} and P_{2A} measured. The quantity Y is then calculated:

$$Y = \frac{P_{1B}P_{2A}}{P_{1A}P_{2B}} \qquad (1)$$

---

[4] Beheim,G. and D. Anthan, "Loss-compensated optical sensor systems", Applied Optics, Vol. 27, No.13, p.2767 and p.2775, 1988.

Figure 3.13 - Lead Insensitive Rod Waveguide Configuration



Y varies monotonically with the fuel level x and is independent of the attenuations in all four lead fibres as seen from the theoretical expression for Y:

$$Y = \frac{(\alpha_T + \alpha_f)\ (1 - \exp(-(\alpha_T - \alpha_f)x))}{(\alpha_T - \alpha_f)\ (1 - \exp(-(\alpha_T + \alpha_f)x))} \qquad (2)$$

where α_T is the attenuation coefficient for pump light travelling down the probe, and α_f is the self-attenuation coefficient of the fluorescent fibre.

Near x = 0, the readings P_{1A} and P_{2A} will be very small and hence have a large relative uncertainty causing increased uncertainty in Y. The top few centimetres of the probe can be left permanently out of the fuel to avoid the high uncertainty region since a certain inactive region is required to develop a uniform distribution of the source light in the rod. However, for the aircraft application, the sensors which are normally mounted vertically in the tanks often in the wings, cannot protrude and would require some form of 90 degree coupling.

3.4.2 Notched Rod Lead Fibre Insensitivity

The same lead fibre insensitivity scheme can be used for the notched rod sensors as shown in Figure 3.14. The quantity Y is calculated as before:

$$Y = \frac{P_{1B}P_{2A}}{P_{1A}P_{2B}} \qquad (1)$$

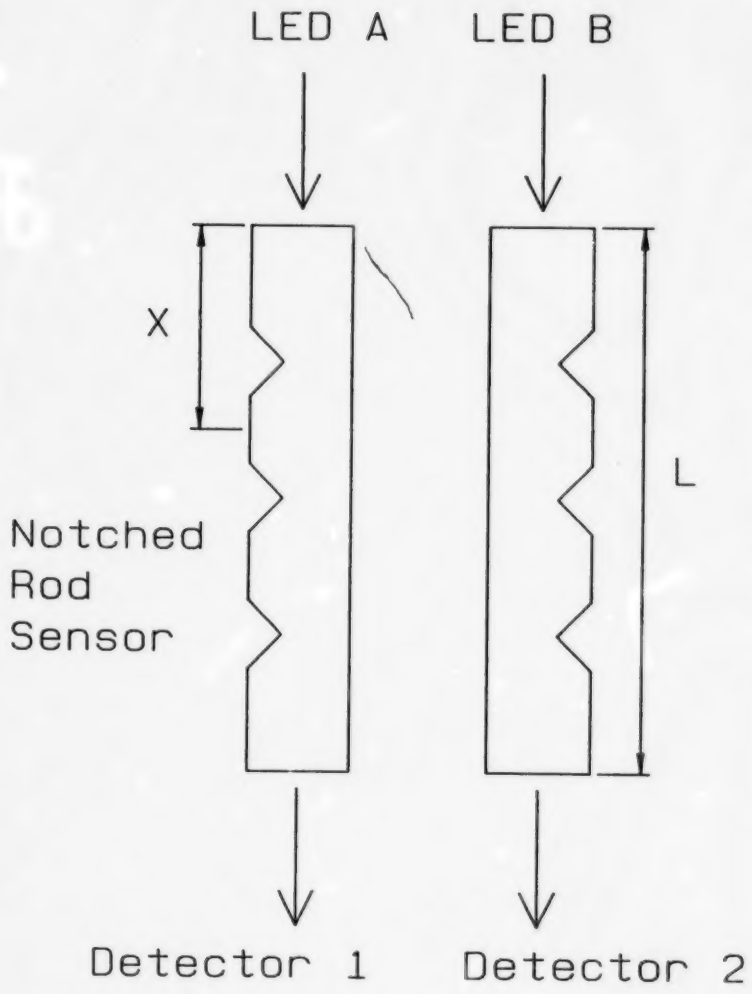
The theoretical expression for Y is much less complex however:

$$Y = k^2x^2 \qquad (3)$$

where k is a constant and hence the square root of Y varies linearly with liquid level.

In this configuration, P_{1A} and P_{2B} are independent of the liquid level. Unlike the rod waveguide, the notched rod does not suffer from a high uncertainty region near the top of the probe when the lead insensitivity is implemented.

Figure 3.14 - Lead Insensitive Notched Rod Configuration



4. TEST RESULTS

4.1 Test Facility

An automated, instrumented test facility (Figure 4.1) was constructed which permitted basic performance testing of probe prototypes up to 1.5 metres long. This facility consisted of:

- a vertical cylindrical aluminum test tank for housing the prototypes,
- a pump and a fuel reservoir,
- a benchmark level sensing scheme for the test tank, including a pressure transducer for continuous level measurement, five float type reed switches for pump limit switches and fixed point referencing and a sight glass for calibration of the pressure transducer and the reed switches,
- a PC based data logger and pump controller using a commercial 8 channel 12 bit analog to digital converter with I/O capability for pump control, and
- an LED or laser driver light source, and PIN photodetector based detection circuitry using lock-in amplification.

The final version of the electronics was almost identical for the notched rod and rod waveguide prototypes.

Figure 4.2 shows a block diagram of the electronics in the notched rod configuration. As discussed in section 3.4, the lead insensitivity scheme employs two emitters and two detectors. The LEDs are driven by square waves of different frequencies whose amplitudes are controlled such that the reference signals P_{1r} and P_{2r} remain constant. Light arriving at each detector has both frequency components, one of which represents a reference signal and the other a liquid level sensitive signal. Each detector output is fed into two lock-in amplifiers, which selectively amplify signals at frequency A and frequency B respectively, effectively separating the two frequency components. The quasi DC outputs of the four lock-in amplifiers (each of which represents one of the parameters in the lead insensitivity equation) are sampled by a multiplexed analog to digital converter and the lead insensitive parameter is computed, displayed, and logged to disk by the microprocessor.

After construction of the test facility, it was necessary to calibrate the pressure transducer and the level switches to form a benchmark for the optical level sensors.

Figure 4.1 - Test Facility

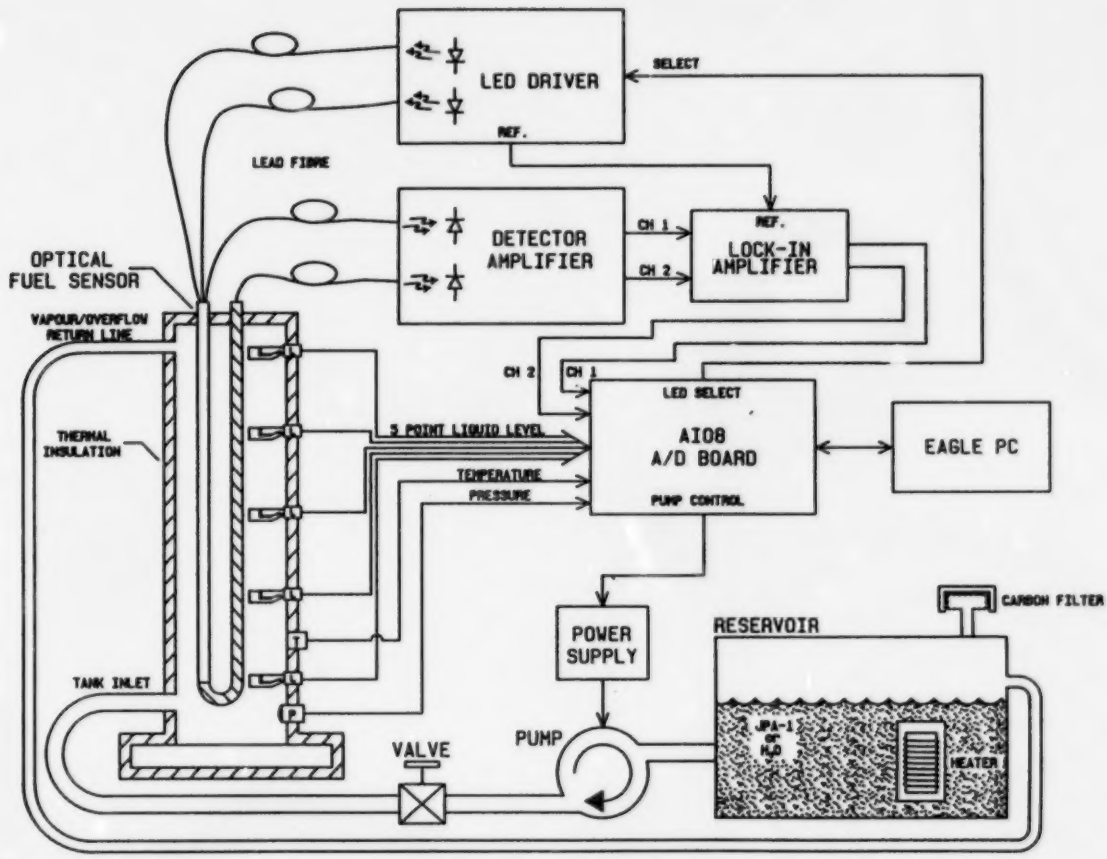
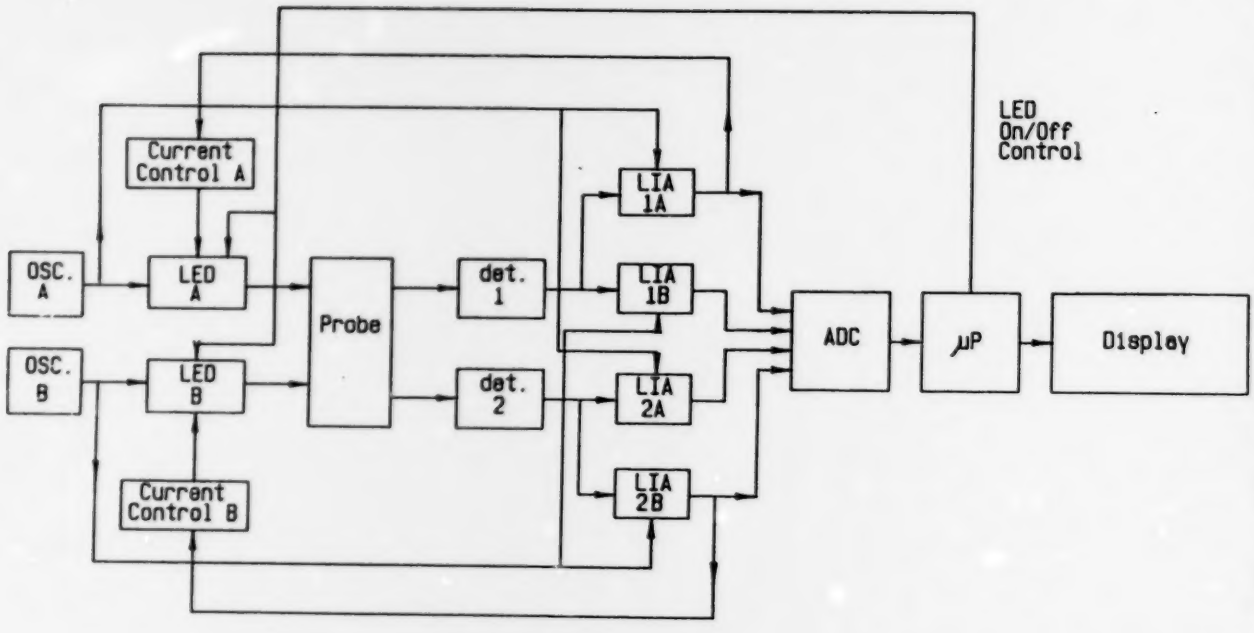


Figure 4.2 - Block Diagram Of Sensor Electronics



Calibration was first carried out using water. The pressure transducer output was measured against sight glass readings. A best fit line was applied to the curve, giving two parameters characterizing pressure response: offset (transducer output with zero level) and slope (volts per psi). Using these numbers plus the known values for density of water and acceleration of gravity, the linearization yielded agreement with the sight glass readings to within two millimetres. The value of slope did not change over time, but offset was seen to vary by as much as 1 cm over 24 hours.

The five level switches were used as references to periodically check the pressure transducer calibration and as limit switches to control the pump.

The pressure transducer was recalibrated for use with jet fuel (JP A-1) simply by modifying the value of density from 1 g/cm^3 to 0.803 g/cm^3, a value determined experimentally.

4.2 Test Plan

Once the prototype fuel level sensors were constructed, two levels of testing were required:

- verification and optimization of the basic sensor performance in terms of its optic, electro-optic, and electronic components

- verification of its performance re the specific application.

Those items which were measured are listed in Table 4.1. The outstanding items from the generic specification are environmental ones: pressure, shock, vibration and acceleration. The key environmental parameter of temperature was however addressed at both system and component levels. The omitted specifications are more dependent on the final packaging arrangement and are addressed in the development specification.

Rather more significant is the potential problem of fouling through the adhesion of foreign material or other degradation of optical surfaces in contact with the liquid to be sensed. Potential sources of fouling can be biological (fungal), lacquer deposits, and chemical clouding. Various coatings were tested both in the test facility along with the sensor prototypes and separately through prolonged exposure to fuel and its vapour in the point sensor configuration.

TABLE 4.1

TEST PLAN

	SENSOR	LEADS	SOURCE/DETECTOR
OPTICS	light levels temporal stability performance in water & fuel mixture response linearity resolution error fluorescence stability	lead insensitivity performance: light levels, range, computational requirements	
ELECTRO-OPTICS	-	-	basic performance SNR AC detection
ELECTRONICS	-	-	
MECHANICAL	suspension fabrication manufacturability	connectors	-
ENVIRONMENTAL	temperature fouling 1 - sensor fouling 2 - material chemical compatibility	temperature	temperature
SPECIFICATION VERIFICATION	accuracy/sensitivity length lifetime estimates (failure mode analysis) size/geometry weight	cable requirements	gauge interface power size weight

4.3 Rod Waveguide

4.3.1 Testing in Water

The first rod waveguide prototype was tested solely in water. Optical power levels of the output signals were quite low (Table 4.2), but after some improvement in the detection electronics and the incorporation of signal averaging it was possible to obtain liquid measurement curves such as that shown in Figure 4.3, which depicts the behaviour of the lead insensitive result Y versus changing liquid level as measured by the pressure transducer. Although it had poor signal to noise ratio, this prototype demonstrated the general principle of operation, exhibiting sensitivity to liquid level over its entire 120 cm length. Y decreases monotonically with increasing liquid level to about 110 cm at which point the trend reverses and Y increases with liquid level. This "boot" in the sensor response curve is due to a departure of the liquid sensitive components of Y from exponential behaviour near the top of the probe, where the pump light is injected and has not yet filled the waveguide.

A second rod waveguide prototype was constructed to increase received optical power levels so as to allow a more accurate and complete characterization of sensor performance.

Figure 4.4 shows a plot of Y versus water level as measured by the pressure transducer as the test tank was pumped full and allowed to drain. The noise was considerably reduced over that in the first probe of this type. The nonmonotonicity of sensor response witnessed in the earlier prototype is once again evident. The drain curve nearly replicates the fill curve, indicating very little hysteresis. Condensation of water on the probe contributed to the temporal instability of this model, requiring that the lid of the test tank be left slightly ajar.

4.3.2 Testing in Jet Fuel

Figure 4.4 also shows a plot of Y versus jet fuel (JP A-1) level as measured by the pressure transducer as the test tank was filled and allowed to drain. The response of the sensor in jet fuel is similar in nature to that in water except that the extinction ratio ,i.e. Y[full]/Y[empty], is smaller. This is due to the refractive index of the jet fuel more closely matching that of acrylic, making it more effective than water at stripping light from the acrylic rod according to the design optimization.

Condensation did not prove to be a problem because instead of beading in droplets, the jet fuel tended to wet the probe with

Table 4.2

Light Levels For Rod Waveguide Sensors

Probe		Launch	Receive	Loss	Theory	Difference
12.7 mm	P1A	-28 dBm	-59 dBm	-31 dB	-27 dB	-4 dB
dia	P2A	-28	-66	-38	-36	-2
	P1B	-26	-53	-27	-24	-3
	P2B	-26	-67	-41	-38	-3
19.1 mm	P1A	-11	-43	-32	-27	-5
dia	P2A	-11	-49	-38	-31	-7
	P1B	-14	-41	-27	-22	-5
	P2B	-14	-58	-44	-31	-13

Figure 4.3 - Water Level Response For First Rod Waveguide

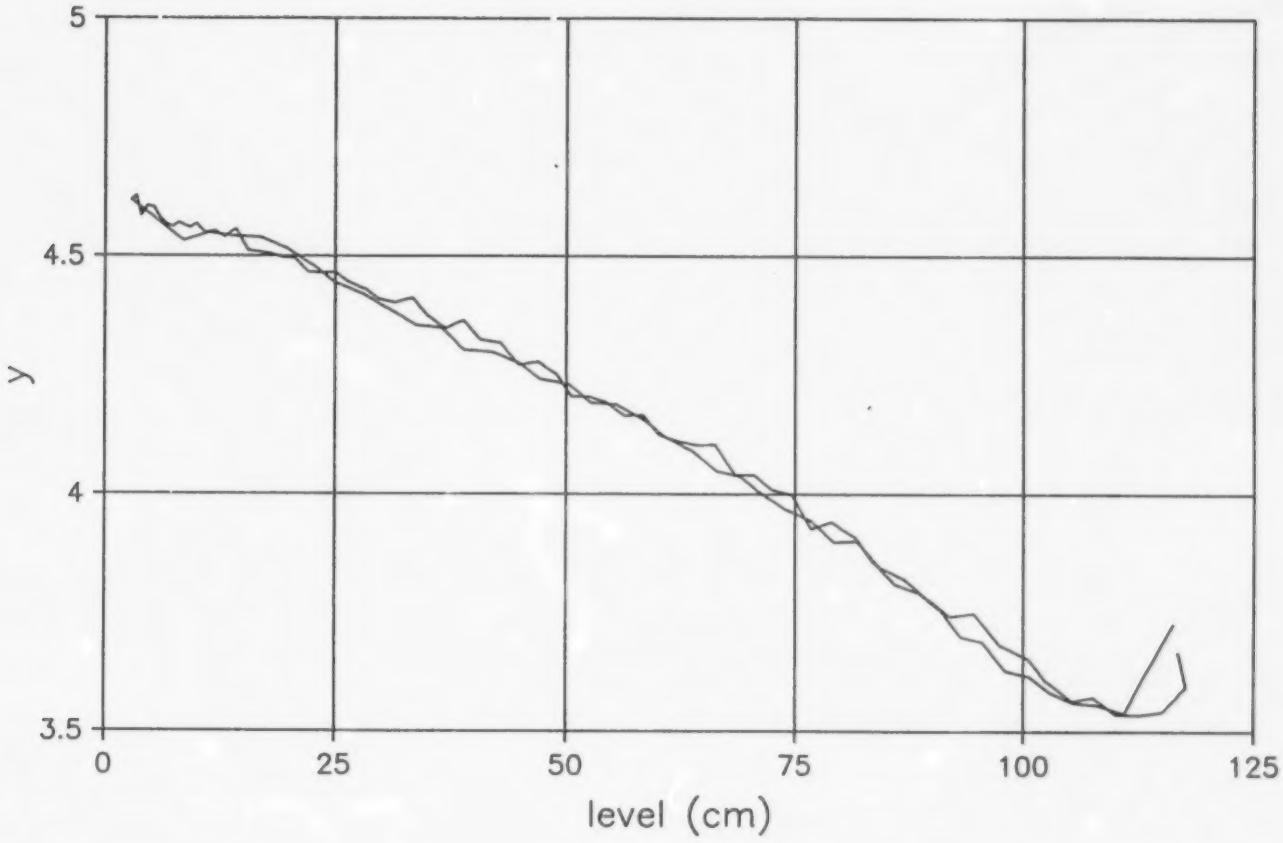
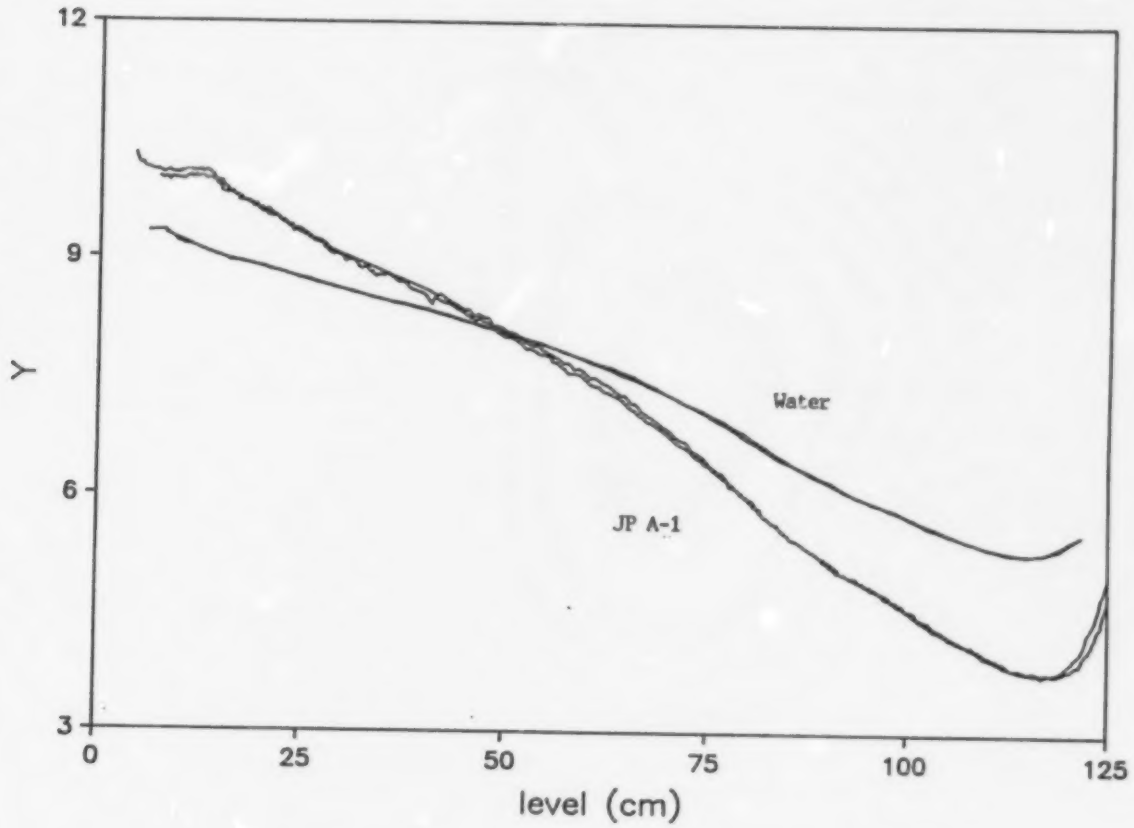


Figure 4.4
Water And Jet Fuel Level Response For Second Rod Waveguide



a thin uniform film, hence it was possible to conduct tests with a sealed tank. This film did cause some instability of the "dry" level of the sensor. If the probe were allowed to stand in an empty tank for an extended period after it had been wet with fuel, Y would drift down to a lower value. The fuel film tends to smooth any irregularities or roughness on the surface of the probe, so as the probe dries, Y decreases. Figure 4.5 shows Y versus time after the probe had been wet, demonstrating the drying effect.

4.3.3 Simulated Fouling

An experiment was carried out in order to characterize the possible effects of optical fouling of the sensor. First, a reference curve was obtained by cycling the water level in the test tank with no simulated fouling applied to the sensor. Two annuli of black electrical tape were placed on the probe from 42.5 cm to 48.9 cm and from 86.6 cm to 88.5 cm, and sensor response with water level was recorded. The tape was then replaced with a translucent silicone grease in the same areas and another recording of sensor response was taken.

The results are shown in Figure 4.6. Black electrical tape obviously has a much more serious effect on the sensor performance, inducing water level error as large as 80 cm and making the probe insensitive below 50 cm. The effect of silicone grease appears more subtle since the sensor retains sensitivity to level along its entire length, yet the water level error is as large as 12 cm.

4.3.4 Sensor Failure

The second rod waveguide sensor eventually failed after exposure to jet fuel and its vapours for only 12 hours. The epoxy used to pot the fluorescent fibre in place was found to be unsuitable for use in jet fuel as it became brittle and tended to detach from the acrylic rod. This left a small section of the fluorescent fibre at the top of the probe exposed to jet fuel vapours, which caused the attenuation of the fluorescent fibre to increase by approximately 3 dB over 5 days. The probe was removed from the test tank, but continued to degrade, until after 7 more days, the optical power levels were diminished by as much as 7 dB. The bare spot at the top of the probe was resealed and the probe was retested. The response of the probe proved identical in form to that before degradation, but light levels continued to change over time due to the effect of jet fuel on the fluorescent fibre, and so testing on this prototype was halted.

Figure 4.5 - Jet Fuel Drying Effect For Rod Waveguide

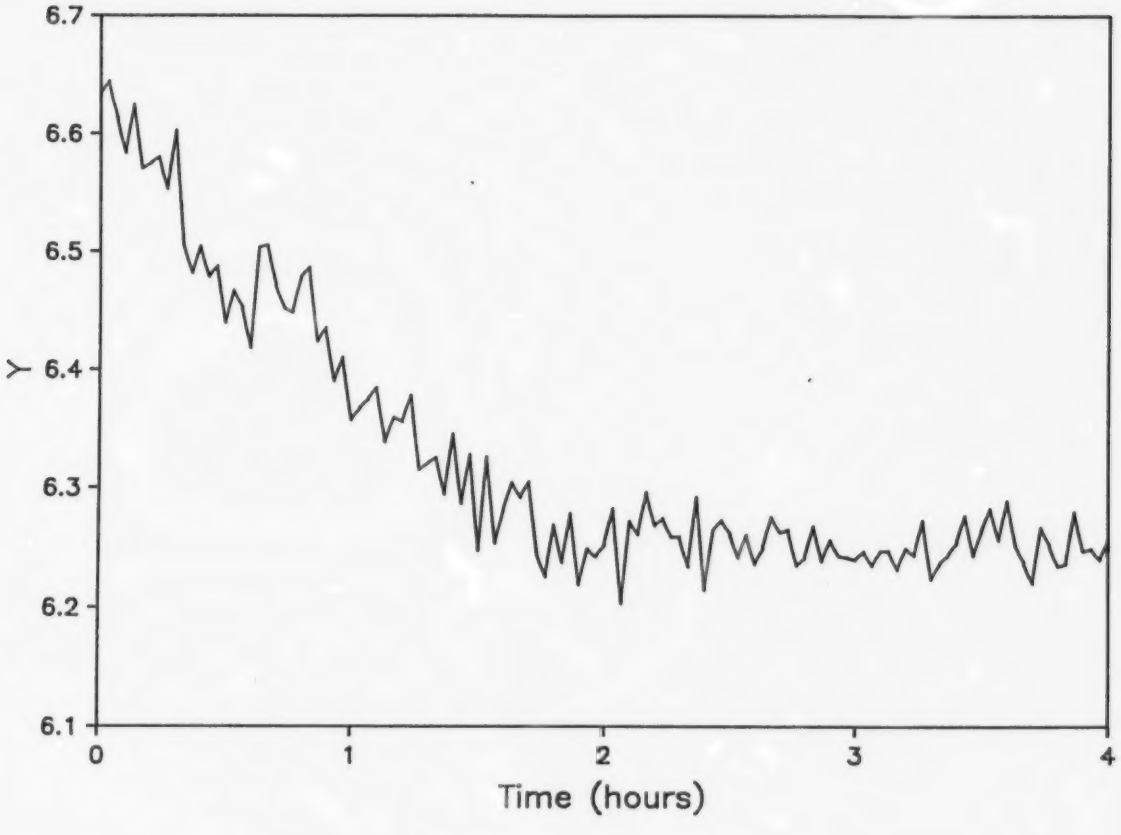
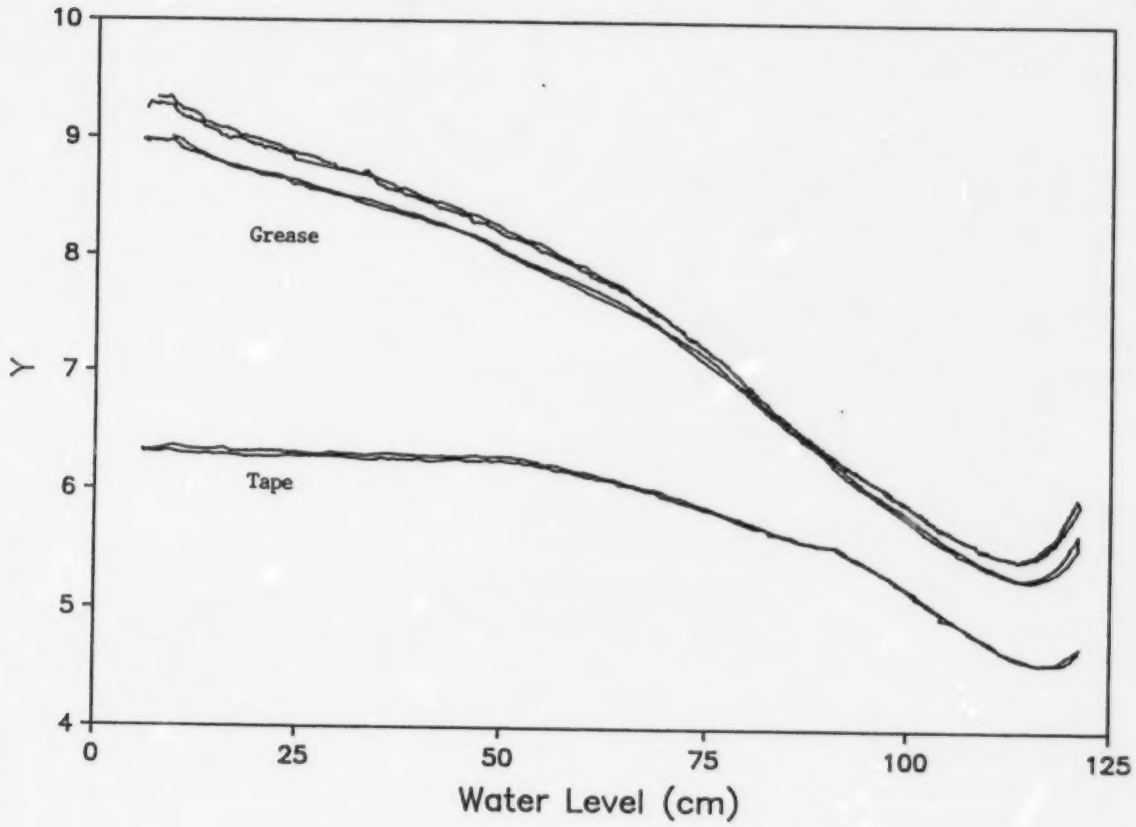


Figure 4.6 - Simulated Fouling Of Rod Waveguide



4.3.5 Fluorescent Fibre Temperature Test

Consideration was given during the design development to any potential temperature sensitivity of the signal conditioning circuitry, most notably by the inclusion of low temperature coefficient and military specification components. Indeed the signal conditioning did not contribute noticeably to the system noise or drift as determined by systematically looping back each of the key components with the sensor removed or by replacing the sensor with optical fibre jumpers. The temperature coefficients of the optical sources and detectors were also well defined and the LED and laser diode current controllers were subsequently compensated to provide a constant optical output. Only the fluorescent fibre's temperature properties were uncertain.

Consequently a simple experiment was designed to monitor the optical power from one end of the fluorescent fibre as a function of temperature. The result was less than 0.1 dB change over a temperature range of 0 to 60 degrees Celsius.

4.4 Notched Rod

4.4.1 Testing in Water

Early testing used 780 nm laser diodes as the optical sources A and B and commercial lock-in amplifier boards. This electronic scheme, which alternately enabled source A and source B for 2 second intervals, was found to be prone to long term drift due to the slow switching between sources making it impossible to employ effective optical power stabilization. Later testing used source drive electronics which continuously modulated source A and source B at different frequencies, allowing optical power stabilization by standard feedback techniques. Although the first method tended to drift over a few hours, it was sufficiently stable during the time required to cycle the test tank to allow sensor response tests.

Figure 4.7 shows a plot of Y versus water level for the first notched rod sensor. The lead insensitive parameter Y decreases monotonically with increasing water level over a 71 cm length, but the curve is not strictly linear due to irregularities introduced during fabrication, most notable of which is inconsistency in the quality of the solvent weld along the V-waveguide.

4.4.1 Testing in Jet Fuel

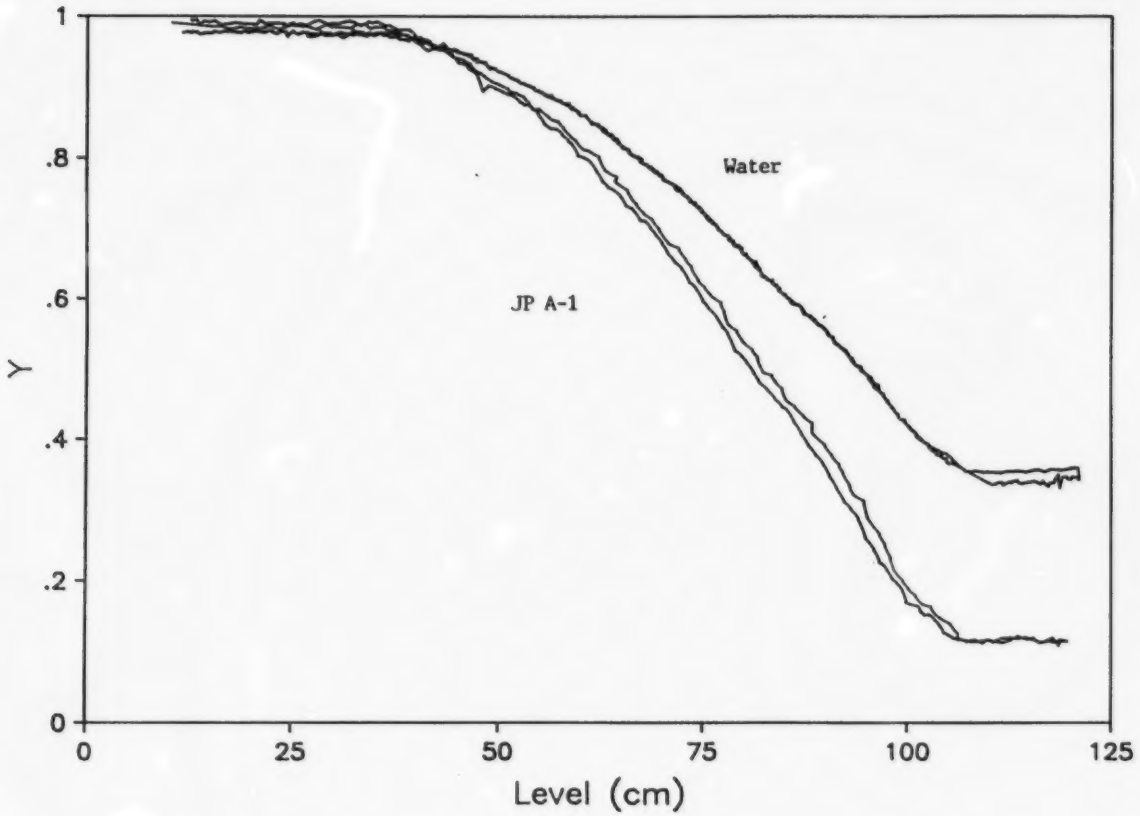
A plot of the lead insensitive parameter Y versus jet fuel (JP A-1) level is also shown in Figure 4.7. Sensor response is similar in character to that in water, but again because the refractive index of the jet fuel more closely matches that of acrylic, the extinction ratio Y[full]/Y[empty] is smaller.

Table 4.3

LIGHT LEVELS - NOTCHED ROD

	Launch	Receive	Loss	Theory	Difference
P1A	-8.2 dBm	-57 dBm	-49 dB		
P1B		-71 dBm	-63 dB	-55 dB	-8 dB
P2A	-7.9 dBm	-68 dBm	-60 dB	-55 dB	-5 dB
P2B		-56 dBm	-48 dB		

Figure 4.7
Water and Jet Fuel Response For First Notched Rod Sensor



4.4.2 Simulated Fouling

An experiment similar to that discussed in section 4.3.3 was carried out on the first notched rod probe. Two sections of the liquid sensitive area (53.4 - 59.5 cm and 86.2 - 91.3 cm) were masked with black electrical tape, and sensor output versus water level was recorded. The tape was replaced with silicone grease in the same areas and response was remeasured. Finally, the sensor face was washed free of grease and a non-fouled response curve was obtained.

These three response curves are shown in Figure 4.8. Again black electrical tape had the greater effect on sensor performance. Level sensing error was approximately equal to the length of tape above liquid level, with a maximum error of about 15 cm. Silicone grease was found to be roughly half as effective a foulant as the tape, yielding a maximum error of 7 cm. As with the rod waveguide sensor, fouling caused greatest error when the test tank was empty. In contrast, the full tank reading of the notched rod sensor under simulated fouling remained reasonably accurate.

4.4.3 Sensor Failure

Failure of the first notched rod probe occurred after 13 days of exposure to jet fuel and vapour when the sensor lid was accidentally broken off during removal of the probe from the test tank. The epoxy had once again released from the acrylic, allowing a small amount of jet fuel to penetrate to the interior of the enclosure, consequently causing crazing of all solvent welds, including the critical welds which formed the V-waveguide. The solvent weld procedure had weakened the acrylic, leaving it susceptible to attack by jet fuel vapour. After this crazing occurred, no further tests could be done using this probe.

4.4.4 Further Testing in Jet Fuel

The second notched rod prototype was tested solely in jet fuel (JP A-1). Sensor response is shown in Figure 4.9. The improvement in V-waveguide solvent welding is apparent by increased linearity and sharper transitions at the onset of liquid sensitivity.

Figure 4.9 is actually comprised of two curves. The upper curve was recorded first while the tank was filled and emptied, and the fill and empty curves retraced each other to within the noise level. The lower curve was recorded after 6 days, during which the sensor was immersed in jet fuel. This curve replicated the first to within 2%. However, a magnification of this plot, as in Figure 4.10, revealed that the variation was primarily due to an offset in the x axis, i.e. it was caused by an offset drift in the pressure

Figure 4.8 - Simulated Fouling Of The Notched Rod Sensor

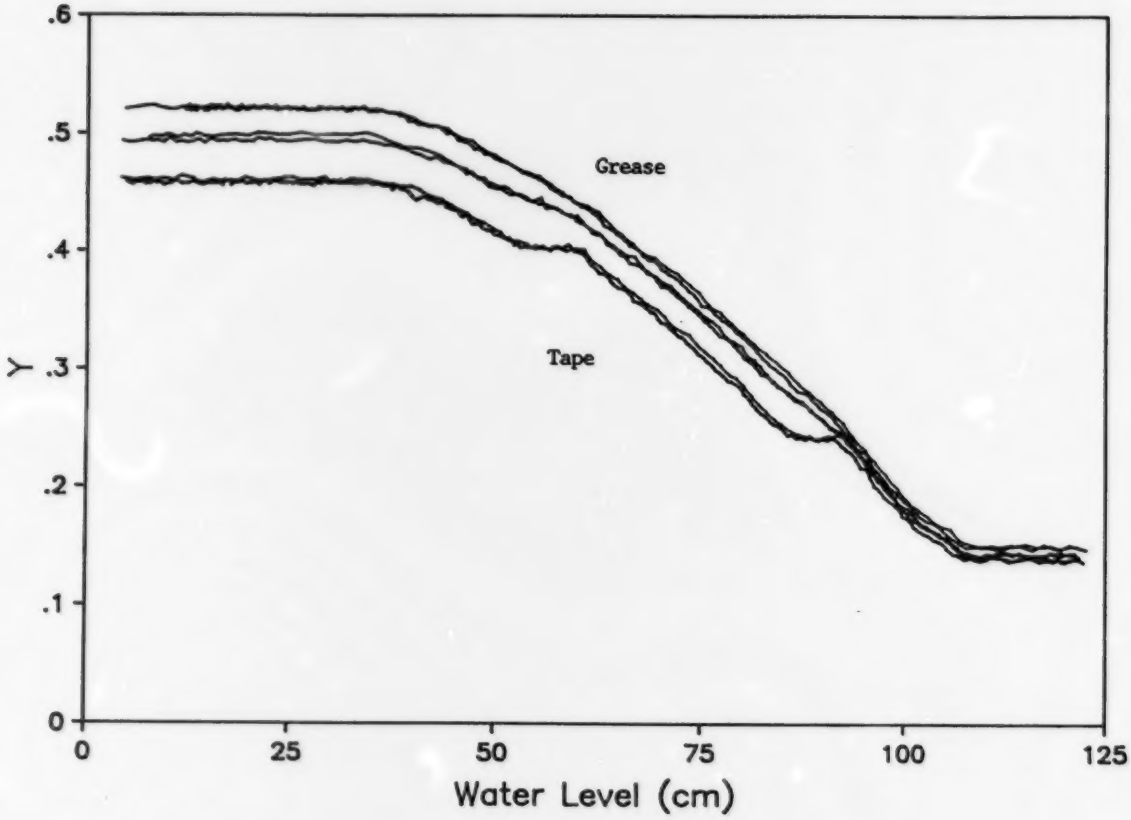


Figure 4.9 - Second Notched Rod Sensor In Jet Fuel

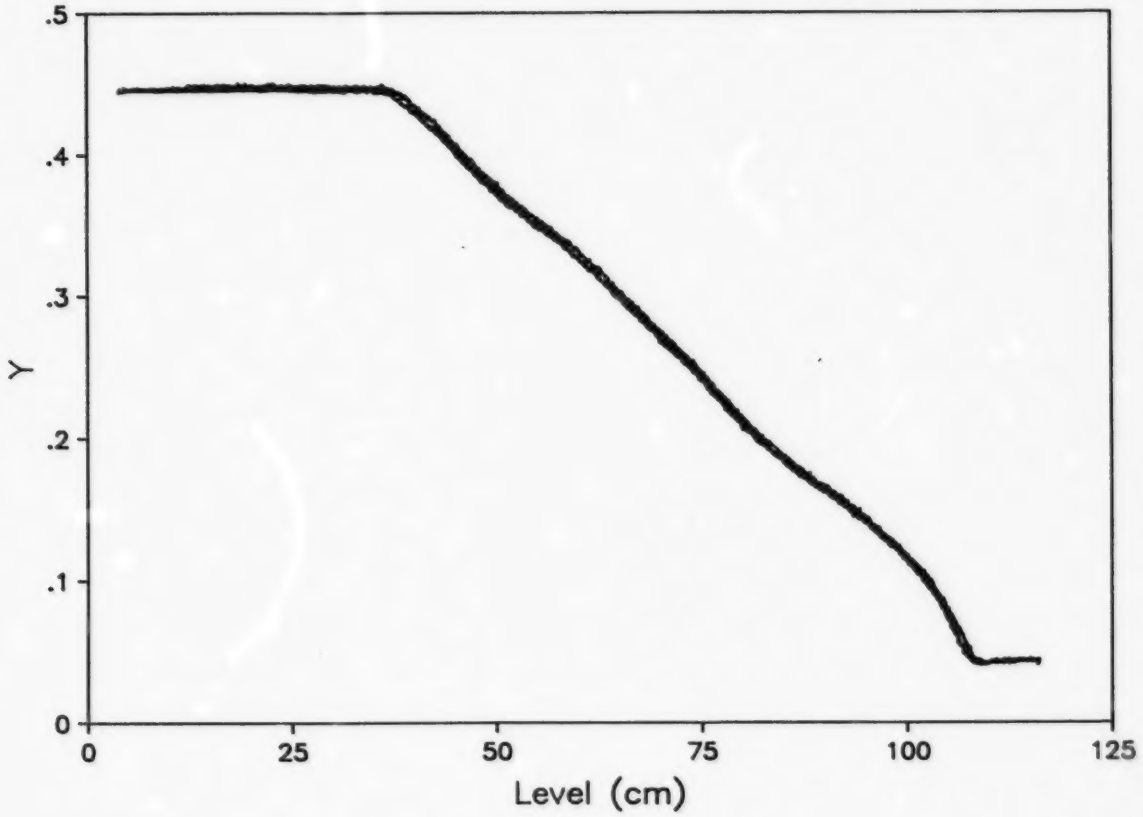
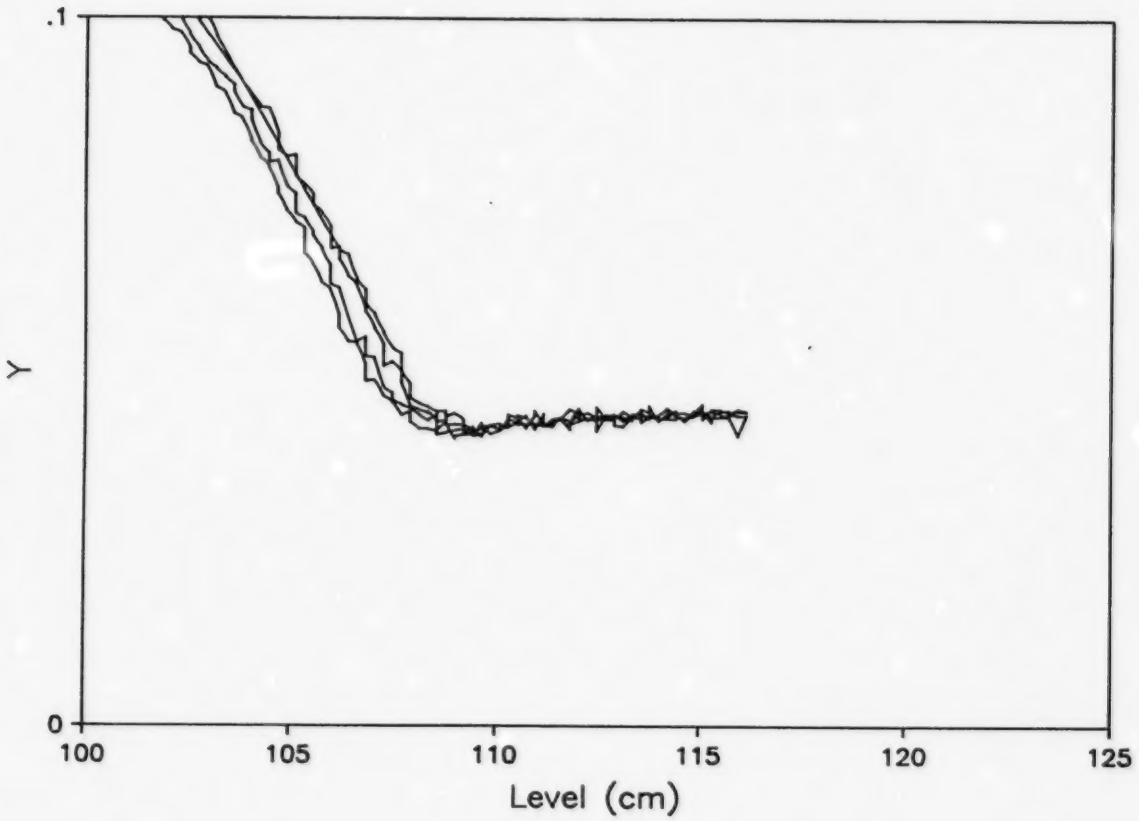


Figure 4.10 - Limitation Of Pressure Transducer Reference



transducer and was not due to a change in the notched rod sensor output. The offset in x was only 0.65 cm, which was typical of day to day variations in the pressure sensor and a limitation for long term testing.

An example of the four optical components which make up the lead insensitive value, Y, for this sensor according to equation (1) and Figure 3.14 are provided in Figure 4.11.

Long term drift tests conducted over several weeks indicated a stability of better than 1%. These same tests also uncovered a temperature dependent variation in the lead insensitive parameter Y of approximately 0.25%/°C. Measurement of the spectral attenuation characteristics of acrylic, and consideration of the wavelength shift of LEDs with temperature of typically 0.3 nm/°C revealed that this temperature drift is due to a red shift in the LED wavelength with increasing temperature, which effectively increased the throughput of the liquid sensitive signals because of decreased attenuation in the bulk acrylic at longer wavelengths (Figures 4.12 and 4.13).

A temperature coefficient of 0.25%/°C is unacceptable for a sensor whose performance specification includes a temperature envelope of at least -30 to 50 °C for the signal conditioning unit. Fortunately there are means by which this temperature dependence can be reduced.

The most obvious solution is to provide temperature stabilization of the electrooptic sources. This can be done by feedback control of thermoelectric coolers, a standard technique in creating stable light sources. Another possibility is to modify the arrangement of source and detector fibres within the probe such that the reference signals pass through approximately the same amount of acrylic as the liquid sensitive signals. This change may be difficult to implement since the reference signals will be much greater than the liquid sensitive signals, hence making it difficult to extract the smaller signal, even using lock-in detection. Another consideration is that the notched rod sensor will ultimately incorporate lasers operating at near infrared wavelengths (780 - 820 nm). Lasers do suffer an identical temperature dependent wavelength shift, but the slope of attenuation versus wavelength is expected to be flatter in the infrared, making temperature induced variations smaller.

4.4.5 Condensation Tests

The problems associated with condensation were observed to be troublesome early on during the testing in water. Consequently an experiment was devised to simulate the condensing conditions seen when an aircraft lands in a warm humid location after the fuel has cooled off at altitude.

Figure 4.11 - The Four Components Of Y: P1a P2a P1b P2b

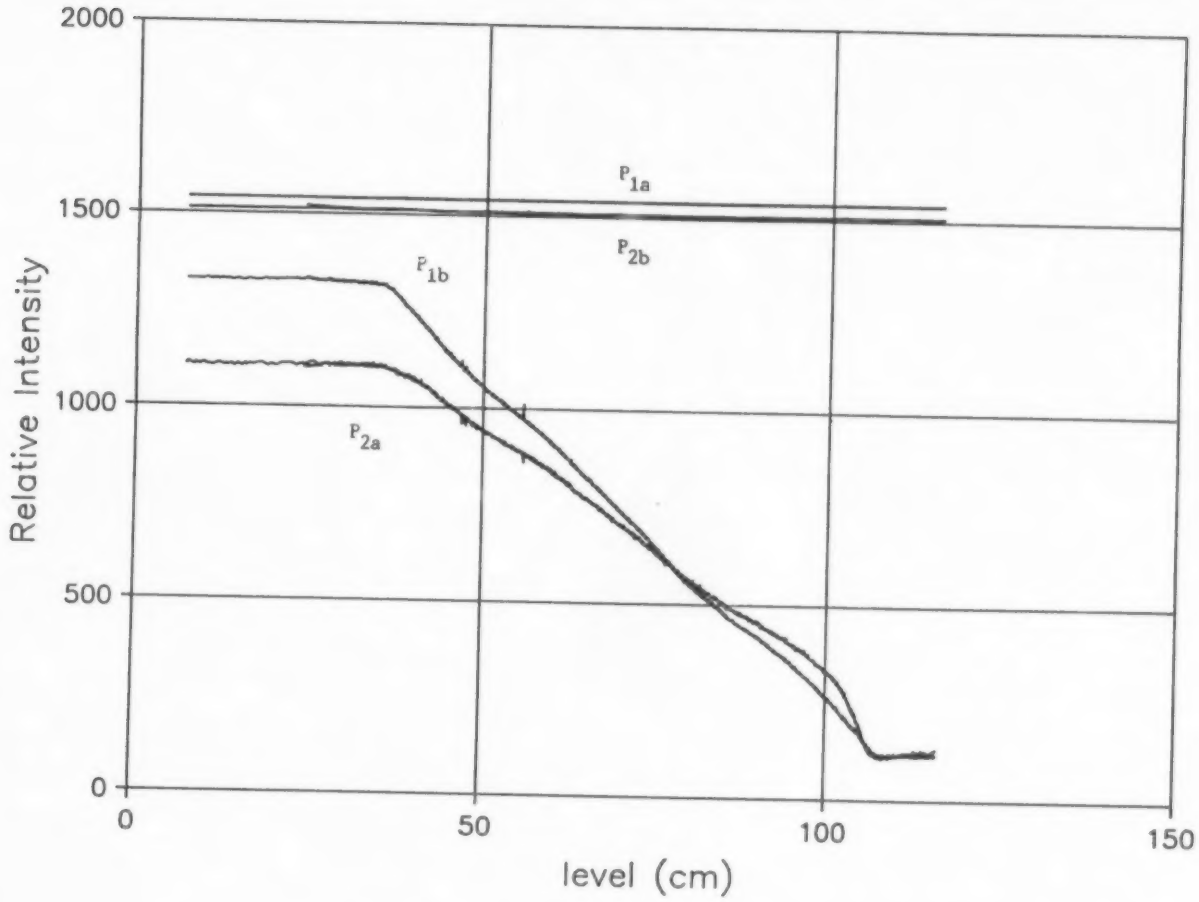


Figure 4.12 - Spectral Attenuation Of Acrylic

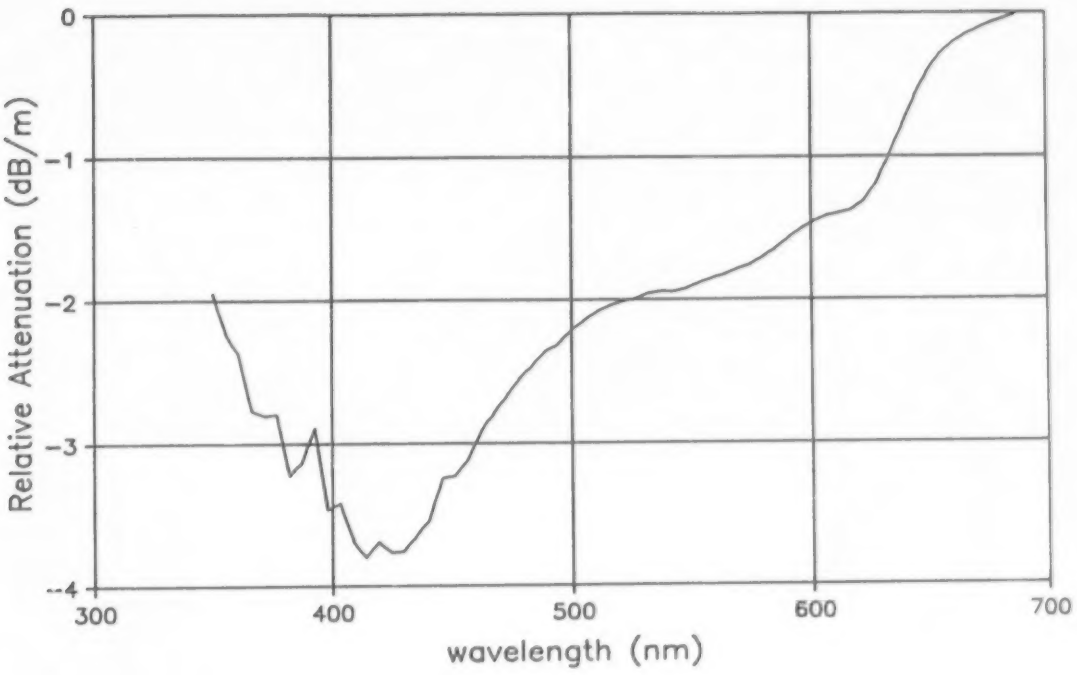
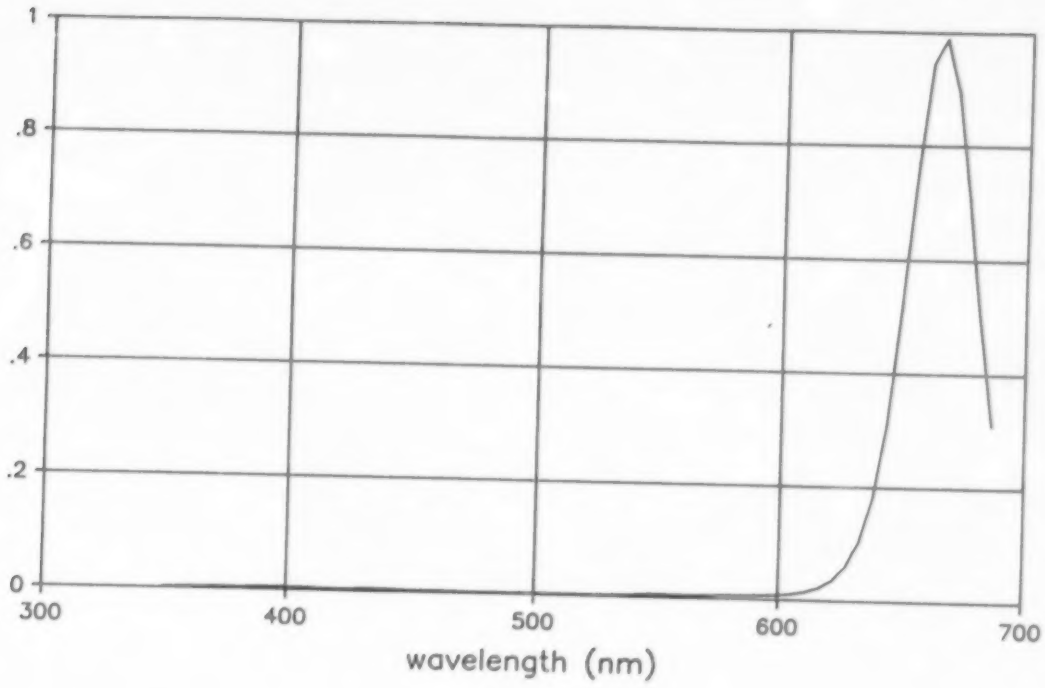


Figure 4.13 - Spectrum Of High Power Red LED



This was done by placing the test tank out of doors on a cold day and then bringing it rapidly to room temperature by closing the overhead door on the loading dock at Focal Technologies. The resulting data for a fixed low level fuel condition is shown in Figure 4.14.

4.5 Lead Insensitivity

The lead insensitivity scheme was tested using the first notched rod probe by incrementally reducing the current to light emitting diodes A and B while monitoring the lead insensitive parameter Y. The results are shown in Figure 4.15, where the normalized output of A and B are plotted with Y against time. No significant change occurred in the value of Y until the light emitting diodes were reduced to less than 20% of their original optical output. The deviation in Y which did occur after this is small in relation to noise, which obviously became dominant as the light levels were reduced further.

4.6 Results Summary and Comparison

A summary of the basic performance achieved for the two sensor configurations is provided in Table 4.4. The results for the notched rod sensor reflect over three continuous months of data.

Table 4.4 - Summary of Sensors' Performance

	NR#2	RW#2
Sensor Length	74 cm	120 cm
Noise	0.7% p-p	0.5% p-p
Drift	< 1% incl. 0.25% / °C	not available
Nonlinearity	± 3%	± 6% + "boot"
Hysteresis	< 0.5%	3%
"Drying"	no effect	6%
Resolution	5 mm	6 mm

The two configurations are also compared in Table 4.5. While the fluorescent rod waveguide configuration is appealing for

Figure 4.14 - Condensation/Frost Effect On Notched Rod

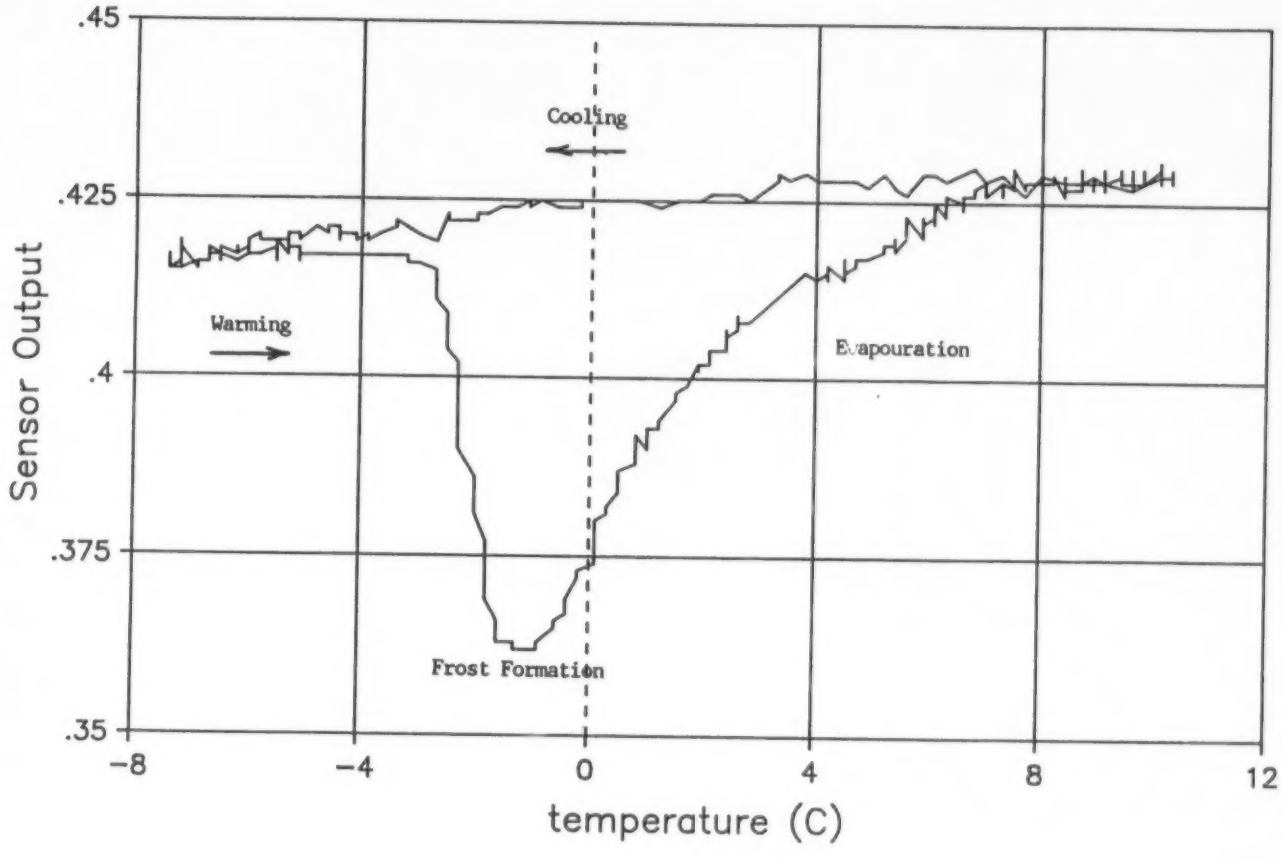


Figure 4.15 - Lead Insensitivity Performance

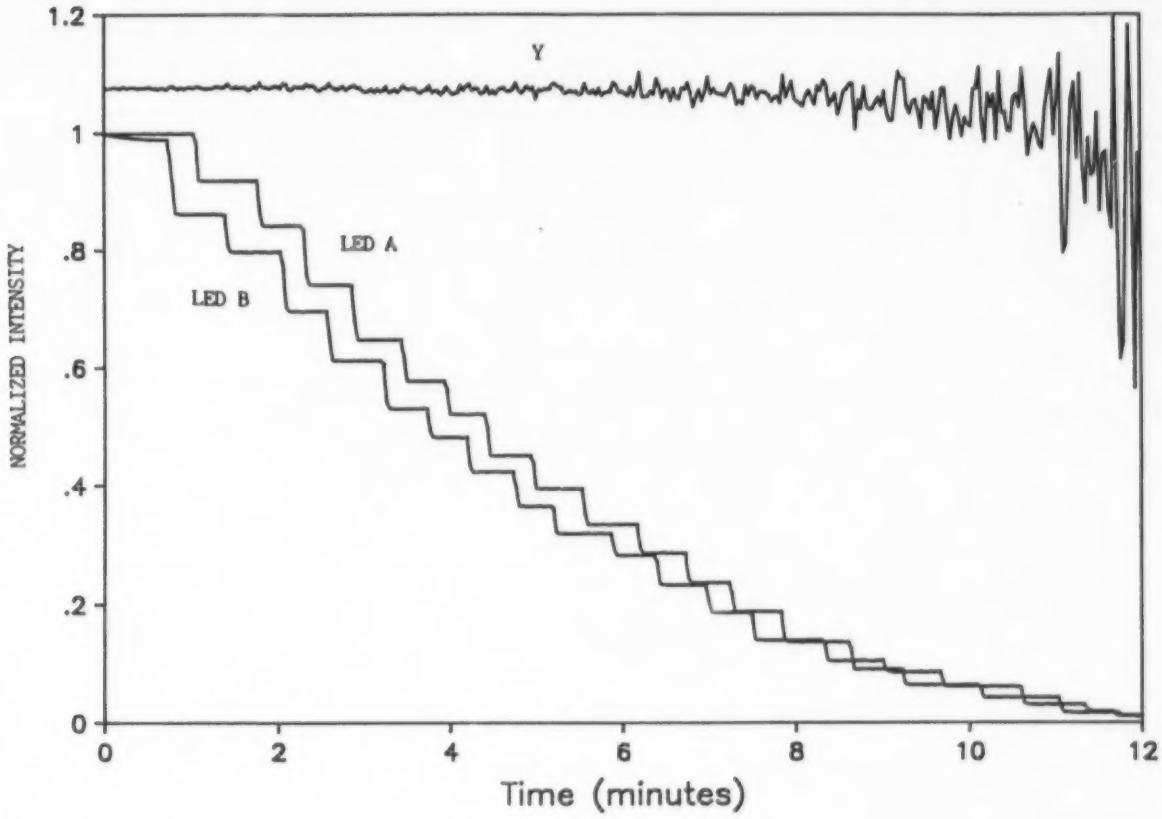


Table 4.5

Candidate Configurations Comparison

	ROD WAVEGUIDE	NOTCHED ROD
GEOMETRY/SIZE (objective)	13 mm dia. rod (+)	2 notched 3 mm dia rods in V shaped waveguide 25 x 50 mm cross section
	(both 1-2 m long)	
COMPLEXITY/ MANUFACTURABILITY	low/high (+)	medium/slightly more difficult
FLUORESCENT FIBRE	yes	not needed (+)
FOULING SENSITIVITY	higher	lower (+)
LEAD INSENSITIVITY	- Same -	
PROTOTYPE STATUS	120 cm demo'd in H_2O & JPA with greed LED, red fluor. fiber, lead insens. scheme	80 cm demo'd in H_2O & JPA, 6 mm dia rods lead fibres, ac detection
DEVELOPMENT REQUIREMENTS	infrared fibre	substrate
	smooth laminate for circular surface	laminate for flat (+) surface fibre coupling scheme size reduced rods
RESPONSE LINEARITY (CALIBRATION)	- both need excitation and detection from opposite ends	
	complex function with exponential terms but smooth; non monotonic boot due to constant light level	simple function (linear) (+)
	non uniform error	uniform error (+)
REQUIRED OPTICAL RESOLUTION	- 90 dBm	- 90 dBm
COST	- both low, slight - advantage to rod waveguide	
(TOTAL +)	(2)	(5)

its apparent simplicity, from a practical and performance perspective the notched rod configuration is by far superior. In terms of parts costs, either sensor could be implemented for less than $200 and similarly for the electronics and electro-optics. If plastics prove satisfactory then simple extrusions and castings would be required at typically $10,000 each and would be suitable for several thousand parts.

4.7 Compensation

On a final point relevant to the FQM application, either fibre optic sensor provides a very accurate volume measurement and can be designed to be relatively insensitive to variations in the refractive index of the fuel. In the case of capacitance probes presently in use, these variations lead to an uncertainty requiring compensation normally provided through continuous measurement of the dielectric constant. However, the density and the dielectric constant relationship of the fuel are not constant and the overall system may sustain an error of up to +/- 4%. An actual density measurement or database is needed to convert the volume measurement to the desired mass of fuel remaining and would be more accurate in the case of the optical fibre sensor based on a more precise measure of volume. Such a database is currently being prepared through a worldwide cooperative effort.

5.0 DEVELOPMENT REQUIREMENTS

The major requirements for further development relate to materials issues, otherwise development is straightforward. Parts costs, the signal conditioning and electro-optic circuitry, suitable fibre optic connectors and specific airframer requirements (Table 5.1) are well defined.

5.1 Materials

There are potentially two key optical materials: the bulk optical material and the primary surface material which can be the same or a laminate. If a laminate, it must be compatible with the refractive index of the bulk material for which the options appear limited to:

- methyl methacrylate (acrylic)
- polycarbonates (Lexan)
- fluoropolymers (Teflon)
- silica or vitreous quartz (glass)

This type of optical application for the coatings, laminations, plastics and other waveguide materials considered is unprecedented. In addition to the basic issues of fabrication and whether the necessary geometries and tolerances can be achieved, the issues include longer term performance including fouling in contaminated fuel, and resolution of the condensation issue through coatings or by other means. A scarcity of data from plastics manufacturers regarding these concerns requires that chemical degradation be measured by long term testing of a prototype as is presently underway with the second notched rod probe. The following materials and/or laminates selection criteria were distributed to over twenty plastics manufacturers with little direct response:

- optically transparent at the operating wavelengths
- refractive index ideally between 1.45 and 1.55
- if a laminate or coating then bondable to a suitable substrate such as acrylic or glass
- chemically resistant to jet fuel and its additives
- suitable for use from -65 to 70 degrees Celsius
- demonstrates a smooth wetting/draining surface
- abrasion resistant
- non-nutrient for fungus
- low application or cure temperature

To date, acrylic has not shown signs of increased attenuation while exposed to JP A-1, but the test is still in its infancy compared to the 20 year design goal. A newly announced optical Teflon intended for use in high temperature plastic fibres may be the answer if its wetting properties unlike other Teflons prevent beading of the jet fuel.

Table 5.1

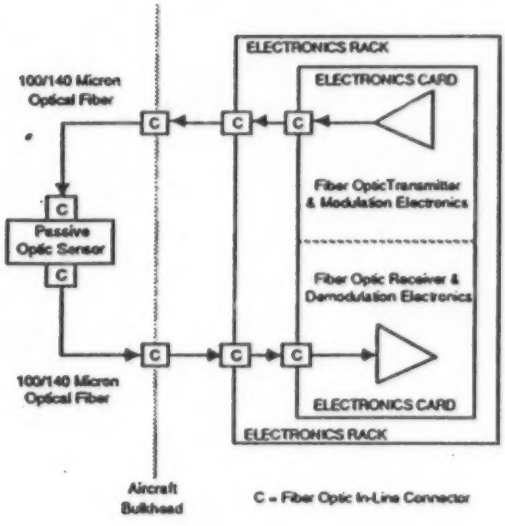
AIRFRAMER STANDARDS

2.1.2 Fiber Characteristics - The following set of fiber optic transmission medium characteristics shall be met to ensure interoperability between sensors and EOAs.

Core Size:	100 micron
Cladding Size:	140 micron
Construction:	Step Index, Glass-on-Glass
Numerical Aperture:	0.29

2.1.3 Connector Characteristics - Each EOA shall have separate optical input and output connectors which shall be compatible with the following:

Contact Type:	MIL-C-38999
Contact Size:	#16 single fiber terminus



LOSS BUDGET ANALYSIS:

MINIMUM INTERCONNECT LOSSES:

Connectors:	8	Connectors
	x 2.0	dB/Connector
	16.0 dB	

Minimum Interconnect Loss: 16.0 dB (1)

ADDITIONAL LOSSES:

Manufacturing Splice:	1.0 dB
Repair Splice:	4.0 dB (2 x 2.0 dB)
Additional Bulkheads:	6.0 dB (3 x 2.0 dB)
Connector Contamination:	0 - 8 dB
Temperature Effects:	2.0 dB
Vibration Effects:	0 - 3 dB
Connector/Fiber Ageing:	2.0 dB
Total Additional Losses:	15.0 - 26.0 dB

Minimum Safety Margin: 15.0 dB (2)

Minimum Loss Budget: 31.0 dB (16.0 + 15.0)

(1) Interconnect Loss Analysis Does Not Include Sensor Insertion Loss or Interconnect Cable Losses

(2) Minimum Optical Safety Margin to Cover Additional Losses = 15.0 dB (Navy A-12 Requirement)

(Courtesy Simmonds Precision)

There remain a number of other improvements which should also be considered before either probe type is ready for implementation.

5.2 Rod Waveguide

Key components of the rod waveguide sensor requiring further development are listed below and discussed in more detail in the following paragraphs:

- a new technique for embedding fluorescent fibre
- an infrared fluorescent fibre
- a laser diode source
- a coating or lamination for the acrylic sensor surface
- the replacement of acrylic as the primary sensor material

Before further testing can be carried out on rod waveguide probes, a new fabrication technique should be devised. The fluorescent fibre has proven to be susceptible to degradation after exposure to jet fuel vapours although accidental, and the epoxy used to embed and protect the fluorescent fibre has proven to be unreliable. The acrylic rod could be cast with a longitudinal hole in which the fluorescent fibre is inserted and potted. This would allow the exterior reflecting surface to remain smooth while ensuring the fluorescent fibre remains protected from exposure to jet fuel.

Optimally, this sensor would operate at near infrared wavelengths for both pumping and emitted light, allowing the use of standard fibre optic sources and silica fibres. As with the notched rod probe, this would yield an appreciable gain in maximum lead length. Due to the intrinsic wavelength dependent nature of fluorescence, this would necessarily be preceded by the development of a fluorescent fibre which has absorption and emission bands falling within the 780 nm to 1100 nm range. Optectron, a French manufacturer of plastic fibre optics and one source of fluorescent fibre, reports that an IR fluorescent fibre is feasible and that they are capable of doing the development. In short, the specification for such a fibre would include:

- absorption peak	near 780 nm
- emission	780-1050 nm or 1000-1700 nm (100 nm FWHM)
- absorption efficiency	≥ 73%
- self attenuation	≤ 3 dB/m (≤ 6dB/m max)
- diameter	250 μm
- numerical aperture	≥ 0.4

5.3 Notched Rod

Key components of the notched rod sensor requiring further development are listed below and discussed in more detail in the following paragraphs:

- size reduction of the notched rods (6.35 mm to 1.59 mm)
- laser diode sources (780-850 nm)
- "cladding" to rid air voids
- metallization or mirroring of the notches
- temperature stabilization of the optical sources
- a coating or lamination for acrylic sensor surface
- the replacement of acrylic as the primary sensor material

A decrease to 1.59 mm diameter notched rods would allow the use of smaller core (200 μm) lead fibres of silica rather than glass, which would in turn extend the maximum lead length from 20 metres to several hundreds of metres. Downsizing the notched rod diameter requires downsizing the notches proportionately, making straightforward machining of the rods an unlikely method of fabrication, hence another method must be found. To take full advantage of small core glass lead fibre requires the use of a high power near infrared light source such as a laser diode.

Air gaps in the most recent version of the notched rod sensor ensure that light remains guided within the notched rods and V-waveguide. Unfortunately, this arrangement is susceptible to vibration and shock, and is prone to leakage under pressure. One solution is to fill these voids with a low refractive index material which would simultaneously clad the light probes and provide structural integrity.

An analysis of the reflecting properties of the notches cut in dielectric acrylic has revealed that for some incident angles the light is only partially reflected. The lost flux could be regained in part by metallizing the notches, thereby making reflectivity relatively insensitive to incident angle. This would also make it easier to make a filled sensor block since air gaps for the 45 degree notches would no longer be required.

As was described in section 4.4.4, a portion of the drift in the notched rod sensor is attributable to a temperature induced wavelength shift in the light emitting diodes, which causes a change in the attenuation of the acrylic in the sensor. One means by which this problem could be eliminated is temperature stabilization of the optical sources with semiconductor thermoelectric coolers.

Although testing thus far seems to indicate that acrylic can withstand jet fuel soaking in the short term, it may prove necessary to provide a laminate or coating for long term

sensor stability. It may even prove beneficial to replace acrylic altogether. For example, polycarbonate is a high refractive index (more easily clad) plastic with good optical clarity which also has better mechanical properties than acrylic, especially at higher temperatures. It remains to be seen whether or not polycarbonate with attenuation characteristics as good as or better than the acrylic presently used is obtainable.

6.0 CONCLUSIONS

The rod waveguide and notched rod configurations have both been demonstrated as capable continuous liquid level sensors. A considerable effort has been expended through analysis and experimentation to arrive at an optimal design for each scheme, from which laboratory prototypes were built. In each case an iteration was carried out to yield second generation improved prototypes as fabrication techniques were refined. Test results have been obtained from the four models, each lending information to assess the aircraft FQM application and for further improvements.

Although the rod waveguide retains advantages in operational and geometrical simplicity, the notched rod configuration remains the preferred scheme due to its superior performance in terms of drift, linearity, and fouling. The rod waveguide sensor remains a viable option for other continuous liquid sensing applications which may benefit from its more compact geometry and for which fouling is not a primary concern. Either sensor would require a 90 degree coupling for the lead fibres, the equivalent of a prism, to fit the space requirements of aircraft wing tanks.

Basic performance required of aircraft FQM has been achieved, namely < 1% error and drift. A temperature coefficient of 0.25% / °C has been identified whose origin is in the wavelength dependence of the attenuation of acrylic. Methods by which this factor may be reduced or eliminated have been discussed. More detailed testing with an advanced prototype covering the application environment in terms of temperature, pressure, vibration, shock described in section 2.0 is now required.

At the present stage of development, the signal processing unit can reside up to 20 metres from the actual sensor. As was explained in section 4.2, downsizing the notched rods would allow optical leads to be extended to several hundreds of metres using 200 μm silica fibre. Further reduction of lead fibre size to the 100/140 requirement noted in table 5.1 would require a proportional reduction in the size of the notched rods and may prove difficult re tolerances.

The lead insensitivity scheme has been tested and proven effective even with optical power level reduced to the point where noise begins to dominate. A signal conditioning scheme has been designed and developed to the degree that its performance in terms of noise and drift does not limit the overall performance of the system. Although full consideration has been given during development to make signal conditioning insensitive to temperature by design, full testing of the electronics will be required to qualify it according to systems requirements.

The major uncertainty remaining revolves around the choice of sensor material and the possible effect of optical degradation by biological fouling and chemical action. A scarcity of data from plastics manufacturers regarding these concerns require that chemical degradation be measured by long term testing of a prototype as is presently underway with the second notched rod probe. To date, acrylic has not shown signs of increased attenuation while exposed to JP A-1, but the test is still in its infancy compared to the 20 year design goal. A newly announced optical Teflon intended for use in high temperature plastic fibres may be the answer if its wetting properties unlike other fluoropolymers prevent beading of the jet fuel.

Simulated fouling tests have been carried out, serving to demonstrate the potential effects of fouling and to compare the responses of the two configurations. As anticipated, the notched rod configuration was impaired less than the rod waveguide, even though it was treated with almost twice as much fouled area. Although these tests proved useful, more realistic tests in an environment conducive to fungal growth are required, i.e. high temperature and humidity and seeded with fungus.

Finally, the issue of condensation remains a real impediment for this application and adds to the materials concerns. Various antifogging and antiicing coatings developed for other applications may prove beneficial if they can be made to work and to survive in a fuel mixture.

The long term outlook for sensors of this type is complex in that it demands both an operational need or benefit and an operational preparedness and acceptance of the introduction of a new technology. For example, maintenance skills for fibre optic sensors will demand entirely new procedures and tools. Certainly however, aircraft designs now on the drawing board will benefit technically from the introduction of fibre optics.